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PREMISSION AND POSTMISSION SIMULATION STUDIES OF THE FOOT-CONTROLLED MANEUVERING UNIT FOR SKYLAB EXPERIMENT T-020

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16. Abstract

Skylab experiment T-020 was conducted to study the maneuvering capabilities of astronauts using a relatively simple self-locomotive device, referred to as the foot-controlled maneuvering unit (FCMU), and to evaluate the effectiveness of ground-based facilities simulating the operation of this device in weightless conditions of space. This paper reviews some of the special considerations given in the definition and development of the experiment as related to the two ground-based simulators. These simulators were used to train the test subjects and to obtain baseline data which could be used for comparison with the in-flight tests that were performed inside the Skylab orbital workshop. The results of both premission and postmission tests are discussed, and subjective comparisons of the in-flight and ground-based test conditions are presented.

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SUMMARY

This paper reviews some of the considerations given in the definition and development of Skylab experiment T-020, involving an experimental foot-controlled maneuvering unit, with special emphasis on the role played by the two related ground-based zero-gravity simulators. The results of baseline data measurements of the maneuvering performance of five test subjects obtained with these simulators are presented, along with pertinent comments by three of the subjects who were the Skylab crewmen assigned to perform the actual zero-gravity tests inside the orbital workshop.

INTRODUCTION

Interest in maneuvering systems to provide an extravehicular locomotive capability for astronauts as part of future space missions has existed for over a decade and yet, until advent of the Skylab mission, there has been very little actual experience with any such device. Skylab experiment T-020, employing a relatively simple foot-controlled maneuvering unit (FCMU) shown in figure 1, was developed to provide some of the much needed information on which to base judgments relative to practical applications and suitable system designs for possible future operational devices. Emphasis was placed on evaluating mobility or performance capabilities of the operator using this system (1) because its simple design could possibly achieve low cost with high reliability and (2) because there was concern that its simplicity could result in poor performance capability with high pilot workload. Tests were carried out both in the ground-based zero-gravity simulators and in actual weightless conditions of the Skylab orbital workshop (OWS) so as to provide a basis for judging the practicality of ground-based simulators for carrying out future design studies and training activities of similar simplified design approaches.

A general overview of the premission plans for the experiment is given in reference 1 and a summary of some of the preliminary results achieved during the SL-3 and SL-4 Skylab missions is presented in reference 2. The purposes of the present paper are to review some considerations of the experiment definition, not covered in the references,

and to present the results achieved with the two ground-based simulators used in these tests. The results are presented in terms of measurements of several performance parameters for a series of specified maneuvers performed by the test subjects. Subjective comments and formal pilot-rating values for the handling qualities of the FCMU assigned by the subjects are also included. The test subjects included not only the Skylab crewmen but also two other persons associated with the experiment so as to obtain a sampling from a larger group of individuals.

Several persons made significant technical contributions to the conduct of these studies and the preparation of this report. Mr. E. C. Stewart and Mr. R. L. Cannaday of the Langley Research Center were responsible, respectively, for the development and operation of the visual-task and the air-bearing simulators, as well as for the training of the Skylab crewmen in these particular simulators. Mrs. M. H. Mayo, of the Langley Research Center, and Mr. R. W. Neely, of the LTV Aerospace Corporation, made major contributions in the processing and handling of the data for these studies.

DEFINITION OF SKYLAB EXPERIMENT T-020

An astronaut maneuvering system is essentially a device to be used by the astronaut so that he can move about safely in space while detached from his spacecraft and perform primary tasks not related directly to operation of the maneuvering system itself. Such primary tasks could be observing a natural phenomenon of scientific interest at a distance from the influence of the spacecraft or inspecting and repairing some other equipment of importance to the space mission. It appears reasonable to assume not only that the maneuvering system should provide the astronaut with sufficient mobility to perform his primary tasks but also that the system should do so with a minimum of interference to the performance of those tasks.

From the standpoint of mobility, the astronaut may be required to translate over distances from a few meters to, perhaps, several hundred meters. At some point, the astronaut might wish to change his attitude for a better view of his target or to redirect his trajectory so as to arrive at a different target. Furthermore, he might wish to remain clear of the target in a station-keeping maneuver so as to make a close-up observation. On the other hand, he might continue to close with the target at a reduced velocity by using his hands or some other device to make and maintain contact. There are some instances where the astronaut could be required to translate and change attitude within a confined space by using considerable precision so as not to damage a fragile portion of the target or its auxiliary equipment.

From the standpoint of minimizing interference with performance of the primary tasks, the operational procedures and controlling tasks for the maneuvering system should

require relatively little attention by the astronaut. Furthermore, the size, bulk, and location of the system should not interfere with the normal working envelope for his arms and hands.

These considerations of mobility and minimal interference tend to be conflicting elements in the design of a useful maneuvering system. With the exception of the hand-held maneuvering unit (HHMU) experiment of the Gemini project (ref. 3, pp. 91-106), studies of various concepts of potential maneuvering systems, such as the Gemini astronaut maneuvering unit (AMU), appear to have placed emphasis on the mobility considerations. Generally, only relatively complex systems providing translational and rotational control capability coupled with attitude stabilization for the system have been considered. Furthermore, in most cases, the maneuvering systems have been located on the operator's back; the location has resulted in design complication because of the need for integrating the maneuvering system with the life support and communication systems required for performance of the extravehicular tasks. In all cases, operation of these systems has required use of the hands, and the controllers have been located within the general working envelope for the arms and hands.

Experiment Objectives

The FCMU concept placed emphasis on simplifying the system design and eliminating use of the hands for direct operation of the system. Although these steps provided an unrestricted working envelope for the hands and produced savings in size, weight, and cost, it was recognized that reduced mobility with increased pilot workload also resulted. One of the prime objectives of the present experiment, therefore, was to determine the performance that could be achieved with a maneuvering device based on the concept of a minimal system.

Because of an almost complete lack of experience with these locomotive devices in space, there are uncertainties concerning the limitations and artifacts or lack of fidelity of the various types of zero-gravity simulators that can be employed. The second objective of this experiment, therefore, was to obtain a better understanding of the role that ground-based zero-gravity simulators could play in the development and utilization of such maneuvering systems. The importance of such an understanding is based on considerations of the high cost and inconvenience of conducting experimental and training operations in space as compared with ground-based operations.

The conduct of related tests on the ground and in space under similar conditions was planned to meet, at least partially, both of these objectives. Consequently, the ground-based simulator was provided with a full-scale mockup of the inside of the OWS where the in-space tests were to be carried out. Recognition was given, however, to the fact that the in-space tests would be performed within a relatively confined area containing many

illuminated objects which provided useful visual cues. These experimental conditions differed markedly from those which generally would be encountered in typical operational situations outside the spacecraft where a maneuvering unit normally would be used. Therefore, inasmuch as tests could not be made external to the OWS, additional ground-based tests were performed under simulated extravehicular conditions so that the intra-vehicular results could be interpreted in terms of the extravehicular situation with some degree of assurance.

FCMU Design Features and System Characteristics

The basic design feature of the FCMU, as depicted in figure 2, was considered to be the foot controls which were employed to provide hands-free operation of the system. The number of thrusters and their locations were selected on the basis of trade-off considerations of the minimum number of components for system simplicity and the desire for at least adequate maneuvering capabilities without excessive pilot workload. This led to the arrangement of eight thrusters, located beneath and just outboard of the feet, that provided single-axis translation and three-axes attitude control. One unusual aspect of this arrangement was that fore-aft translation was coupled with up-down pitch inputs due to the use of a pair of the fore-aft thrusters which faced in the same direction to produce the pitching moment. Opposing pairs of the fore-aft thrusters were used for yaw control but, in this case, the thrusters fired in opposite directions so that only a pure couple was produced. The up-down thrusters were used for both translation and for roll control.

The assumption was made that the pilot could adequately perform the attitude stabilization functions himself as part of his normal controlling task; consequently, use of a relatively complex stabilization system and the requirements for additional electrical power were avoided.

The operator essentially sat astride a saddle-shaped structure and was fastened to it by a set of body and foot straps. The seat position was adjustable on the FCMU to accommodate the leg lengths of different test subjects. Considerations given to the mass-distribution characteristics for the system dictated location of the propellant-gas supply and its associated equipment in a simple frame strapped to the operator's back so as to minimize cross-coupling motions resulting from roll and yaw control inputs.

The harness system, shown in figure 3, was designed so as to attach both the FCMU and the backpack to the operator without seriously limiting the ability of the operator to bend at his waist; this waist mobility was thought to be a desirable feature. Subsequently, it was recognized that this feature might impose some difficulties for the operator when he attempted to control the system; however, this harness sytem was retained so as to permit an evaluation of its impact on the handling qualities of the system.

Logic for controlling the system was based originally on the balancing reflexes normally employed as a person attempts to maintain a steady standing position by using both feet. Although this logic proved to be usable during the definition studies, the reverse of this logic was found to be more acceptable to persons with aircraft piloting skills and was therefore incorporated into the system for the in-flight tests. Table 1 gives the list of specific input motions for each foot required to produce a desired acceleration command and also identifies the corresponding thrusters activated by the inputs.

Preloaded centering springs forced the control pedals to return to their neutral positions whenever the operator relaxed his control inputs. The thruster valves could be operated incrementally so as to vary thrust proportionally, but the travels were small and the normal input action used was full-off to full-on in a "bang-bang" or pulsed type of control action.

The thruster assemblies were adjustable in the axis parallel with the pitch axis so that the up-down thrusters could be alined with the center of mass of the system in order to minimize pitching motions generated by translation accelerations.

The system was configured originally such that the principal inertia axes were parallel with the thruster axes, defined as the reference axes for the system. However, after the equipment was finalized, refined data for the inertia values of the components were obtained and it was determined that the principal axes were alined about 7° in the pitch-up direction from these reference axes (see fig. 2). In this case, the application of roll-control acceleration by the pilot produced a noticeable cross-coupling motion about the yaw axis, and vice versa. Although reduction of this cross coupling was considered very desirable so as to improve the handling qualities of the system, practical considerations related to mission preparations dictated that the system not be modified. A brief listing of some of the physical characteristics of the system is given in table 2.

Selection of Zero-Gravity Simulators

Consideration of the attributes and deficiencies of various zero-gravity simulation techniques as applied to this experiment led to the selection of two different schemes to be used for training the test subjects and for collecting baseline data. The simulator based on the first scheme provided only three-degree-of-freedom motion and employed an air-bearing supported maneuvering system which operated over a very smooth and level surface. This was referred to as the air-bearing simulator (ABS) and is shown in figures 4 and 5. The test subject experienced the sensations of operating an actual maneuvering system and was able to observe its motions with respect to actual three-dimensional objects. The motions were restricted to only those that occur in either the pitch or the roll plane for any given set of runs and, also, were limited to distances of about 15 meters or less.

The second simulation technique employed a digital computer to determine the orbital motions of the maneuvering system relative to the Earth's horizon and a nearby target spacecraft as the system responded to the test subject's control inputs. The computer drove a projection system that permitted the operator to observe the scene as viewed from the maneuvering unit so that he could make the necessary control inputs to achieve a desired maneuver. This simulation system was referred to as the visual-task simulator (VTS) and is depicted in figures 6, 7, and 8.

A more complete discussion of these two simulators is given in appendix A.

Selection of Typical Maneuvers

In planning the details of the experiment there were numerous maneuvers to be considered; these maneuvers varied in the distance traveled and the number of translational and rotational velocity changes performed enroute and at the termination of the activity. Because of the exploratory nature of this investigation, it was considered impractical and unnecessary to cover all possible combinations of these variables. Furthermore, because of the limited space and allotted time for conducting the experiment within the OWS, there were specific constraints placed on the types of maneuvers that could be performed. Other considerations were the needs to limit maneuvers to those that could also be performed in the simulators and to use only those that could be analyzed to provide meaningful data.

These considerations dictated the selection of a set of relatively short, simple maneuvers associated with the fundamental control capabilities of the system. These maneuvers were always performed in the same sequence: the first four maneuvers involved motions relative to only one control axis at a time; the last two involved motions of a more complex nature. The first three maneuvers involved rotation primarily and were referred to as either pitch-, roll-, or yaw-attitude change and hold maneuvers. The subsequent maneuvers involved translation, but attitude control was also employed. These latter maneuvers were referred to as single-axis, double-axis, and dogleg maneuvers. A more complete description of all maneuvers is given in appendix B.

Although these specific maneuvers did not necessarily represent real tasks in terms of an actual extravehicular activity, it was believed that the selected maneuvers could be used as the basis for judging the operator's performance capabilities for much longer and more demanding tasks.

Performance Guidelines and Measurement Parameters

Evaluation of the maneuvering capabilities for this exploratory investigation was considered to be essentially a qualitative judgment based on the subjective comments of the individual operators and on some specific measurements documenting how the maneuver was performed. In order to support this judgment, it was necessary to establish some

guidelines defining those elements of the experimental maneuvers that were considered by the investigators to be significant.

Performance guidelines.- The imposition of rigid performance requirements for the maneuver itself in terms of time limits or attitude and positional errors did not appear appropriate for most envisioned applications. Consequently, the approach taken was that the operator should be concerned primarily with getting from one position to another while maintaining his attitudes and velocities within reasonable limits as well as taking whatever time was required to perform the task with a reasonable amount of effort. These guidelines were used throughout the training and data-taking sessions and are paraphrased as follows:

(1) No time limit is specified, and the subject has the option as to how to use the available fuel.

(2) The subject should use his own judgment as to what maneuvers he actually can accomplish and what translation and rotational rates he considers to be "comfortable" or "desirable."

(3) The subject may alter or adapt his previously developed piloting techniques as he judges necessary to satisfy conditions encountered in subsequent maneuvers or test sessions. However, in the repeat runs of a particular maneuver for data taking, he should attempt to be consistent.

(4) The subject should identify the initiation and termination of specific phases of each maneuver by use of the cue word "mark."

Performance measurements.- Measurement of the maneuvering performance was based on a few selected parameters that essentially described how the maneuver was performed. These parameters basically show (1) how long the subject took to perform the whole maneuver and particular phases of it, (2) what linear and angular rates were used, and (3) what amount of propellant gas was used to complete the maneuver.

The term "total maneuver time" consisted of the time from the initial mark given by the test subject to the final mark; it did not include the initial positioning time or that used to reposition the subject following the final mark. For those maneuvers involving an attitude or position-holding task, the "hold time" was included as part of this total time; for these same maneuvers, the hold time was recorded as a separate parameter. The difference between the so-called total and hold times denoted the time during which the subject was actually commanding attitude or translation changes; however, this was not recorded as a separate parameter.

The term "maximum linear and angular rates" represented the largest rates sustained throughout the major or significant portion of the positional changing phase for a

given maneuver. These values were considered as being indicative of the desirable or comfortable rates referred to in the guidelines.

The term "total impulse" represented the total quantity of propulsive gas used to initiate, execute, and terminate the maneuver. This included gas used for both the translation and attitude commands inasmuch as the same thrusters are used for both functions.

During the training phase for the test subjects, an additional parameter was used as an index of the degree of foot coordination being developed by the individual as he progressed through the training maneuvers using the VTS. This parameter, named "control mismatch," represents the percentage of the total-control input time in which an input is made using only one thruster rather than two. This was considered generally to represent unintentional and uncoordinated inputs inasmuch as the thrusters were intended to be used normally in pairs for all control inputs.

PREMISSION AND POSTMISSION BASELINE TESTS

The primary objective of the ground-based simulation tests was to obtain a set of qualitative information and quantitative data. These results were to be used as the basis for comparisons with the in-flight experimental data and for interpretation in terms of extravehicular conditions that did not exist in the OWS.

Test Subjects

Two sets of subjects were used for these simulation tests so as to assist in interpreting the limited number of in-flight test runs that could be performed (see table 3). The first set, designated "crewmen," consisted of the three astronauts (subjects 1, 2, and 3). The first two subjects participated in the flight tests and are also designated "flight subjects." The second set of subjects consisted of two research engineers who were responsible for conducting the experiment and also served as instructors during the training session for the astronauts. These two are identified as subjects 4 and 5.

A summary of the total hours of training time in the simulators prior to the taking of baseline data is given in table 3. The two instructors had the opportunity to devote many hours over the period of several years prior to their participation in these test sessions and had become highly proficient in their maneuvering capabilities with the FCMU as represented by the simulators. They also had prior association with the astronauts as part of research and training simulation efforts involved in earlier space missions. However, they had no direct experience with actual spacecraft systems and space flight operations as did the astronauts.

Although the astronauts were qualified as test subjects without question, their training in specific aspects of this experiment and in the unique features and characteristics of

the FCMU was quite limited. It was intended that the premission baseline data would be obtained after each crewman had received sufficient training and practice to stabilize and minimize the variability of his performance parameters. However, practical circumstances, dictated by the press of the crewmen's preparations for their mission, made it impossible to schedule a sufficient number of practice and data sessions to achieve this goal. Consequently, their piloting proficiency with the FCMU simulators was not necessarily as highly developed as that of the other two subjects by the time the initial baseline data were obtained.

Test Procedures and Conditions

Insofar as practical, the same test maneuvers were performed in the same sequence in each of three test conditions by each test subject. Each maneuver was performed at least five times successively by each crew member, with the performance being monitored for apparent anomalies during each run. In cases of an unusual event, such as a blunder or an undesirable rate being generated, at least one additional run was usually performed. The basis for judging such occurrences was primarily the prior experience of the two instructors. In the cases of the two instructors acting as test subjects, each maneuver was performed at least 10 times, rather than 5, in order to establish a broader data baseline.

In the case of the flight subjects 1 and 2, a series of postmission tests were also performed using only the air-bearing simulator and selected maneuvers. These ground-based tests were performed a few months after completion of their individual space flights.

All tests were performed in the shirt-sleeve condition with the subjects wearing lightweight coveralls and shoes. Due to the previously mentioned time constraints for the subjects, no baseline tests were conducted in the pressure-suited condition, primarily because use of pressure suits would have seriously limited the data that otherwise could have been obtained.

The test condition for the VTS was representative of extravehicular activities (EVA) within about 15 meters of the target spacecraft. The spacecraft was assumed to be in circular orbit about 320 kilometers above a completely day-lighted Earth and oriented continuously with respect to the Earth's horizon. Orientation of the subject with respect to the spacecraft and horizon for the start position was altered in some of the maneuvers to provide an appropriate set of visual cues for each particular maneuver. This was done also to avoid a degree of conditioning brought on by the repetitious nature of the test runs performed within a relatively short period.

There were two test conditions for the ABS, the first being representative of the EVA conditions presented in the VTS and the second duplicating those for the intravehicular

activities (IVA) carried out in the Skylab OWS. The starting and stopping positions for the IVA condition corresponded exactly to those planned for the in-flight sessions in the OWS.

Data Measurement

The quantitative data were derived by different methods for the two simulators. In the case of the VTS, the computer was programed to provide a printed tabulation of the desired quantities and trajectory plots at the conclusion of each run. In the case of the ABS, the data were obtained by observers who used stop watches to obtain the time to traverse specific distances and who read a pressure meter in the propellant-supply system to obtain a measure of the gas being consumed. The maximum linear and angular rates for the ABS were based on these time measurements. In general, all quantities were measured for the ABS to an estimated accuracy of about ±5 percent of maximum values. In the case of the VTS, accuracy of the computer-generated data was better by several orders of magnitude.

Pilot-rating values were assigned to each maneuver at the completion of several runs. The rating system was based on the Cooper-Harper system of reference 4 but employed a refined chart, as shown in figure 9. The chart was modified primarily in format from that of the reference to improve readability and facilitate the decision-making process under the conditions of the experiment where time for making the evaluation was limited. The changes that were introduced in the chart were not intended to alter the interpretation of the rating system.

In addition to the pilot-rating values, the test subject was requested during the test session to make comments pertaining to operating characteristics of the FCMU, performance of the maneuvers, influences of the simulation artifacts, and so forth. At the completion of the test session, a final debriefing session was held to obtain further comments.

PRESENTATION OF SIMULATION TEST DATA

The data obtained from both the preflight and postflight tests are presented in figures 10 to 12 for each of the maneuvers given in the sequence in which they were performed. The figures show plots of the mean (circular symbols) and standard-deviation (vertical lines through symbols) values for the total maneuvering and holding times, the maximum angular and linear rates, and the total impulse for the maneuvers performed by each subject in each of the three test conditions. The solid and dashed horizontal lines passing through the groups of symbols denote the mean values for the crewmen and instructors taken as two respective groups. A summary of these mean values is given in table 4.

It is important to note that these data do not necessarily include all of the runs completed by each subject. Inasmuch as these baseline data were intended to be representative

of the subject's typical performance, those runs in which some form of anomaly was noted were deleted. These anomalies were generally the result of either a blunder or a slight change in piloting technique. Quite often in these cases, the subject commented that the motions were either uncomfortably fast or undesirably slow. In no case did these anomalies produce conditions which prevented the subject from recovering and successfully completing the maneuver. The number of runs dropped was about 10 percent of the total number of runs completed.

DISCUSSION AND ANALYSIS OF RESULTS

This discussion and analysis cover several aspects of the tests based on both the qualitative and quantitative results as applied to the specific test conditions. No attempt has been made to interpret these results in terms of extravehicular operational activities utilizing pressurized space suits. The discussion covers the following: relative degree of task difficulty, pilot rating of the FCMU handling qualities, comparison of the EVA results for the ABS and VTS, comparison of ABS results for the EVA and IVA conditions, comparison of the premission and postmission tests, and subjective comments pertinent to the simulation techniques.

Relative Degree of Piloting-Task Difficulty

Although the maneuvers were selected initially on the basis of a sequence of increasing motion complexity, the difficulty of the piloting task could not be expected necessarily to follow in the same sequence because of the possible influence of factors other than the sequence of motions involved. Other such possible influences were: the dynamic control characteristics of the maneuvering system, the various physiological motion cues (such as audio and visual) on which the operator relied for information concerning the execution of the required motions, and the limitations and artifacts of the simulators being used.

Inasmuch as the relative degree of piloting-task difficulty for the various maneuvers performed in the different simulators was judged to be important to an understanding of the test results, an evaluation of this aspect was carried out. The evaluation was based on the subjects' comments in response to specific questions as to the apparent order of difficulty of the maneuvers for the three test conditions of the simulators and as to factors which significantly affected this judgment. There were some differences in opinions among the subjects; consequently, some interpretation was required to complete the evaluation. Inasmuch as the two instructors were intimately involved in the conduct and reporting of this experiment, only the comments of the crewmen were used as the basis of the subjective evaluations.

The six maneuvers for each test condition were rated in terms of their relative degree of piloting-task difficulty, designated "easy," "moderate," and "difficult." The results of this evaluation are summarized in table 5. The following comments pertain to this evaluation:

(1) In general, the dogleg translation maneuver was the most difficult to perform, followed by the attitude control and hold maneuvers with somewhat lesser degrees of difficulty. The double-axis translation maneuver was the easiest to perform.

(2) The task involved in pitching 90^{o} for the attitude change and hold maneuver was more difficult to perform than that performed as part of the double-axis translation maneuver because of a greater degree of precision involved in pitch alinement and also because of greater concern about off-axis drifting.

(3) For a given maneuver, the task performed in the VTS was more difficult than that performed in the ABS.

(4) In the ABS, the IVA task was somewhat more difficult than the EVA task because of the more confined space. Although the additional visual cues for the IVA case made judgment of the motions easier, this additional information caused the subjects to be more concerned about minimizing the small drift rates that, otherwise, were either considered reasonable or went unnoticed.

(5) Exercising simultaneous control of two axes was much more difficult than sequential control of the two axes.

Based on this evaluation, it appears that the various tasks covered a fairly wide range of difficulty and provided an adequate opportunity for the subjects to judge the performance capabilities and overall handling characteristics of the system. Although there were instances of blunders and changes in piloting technique for the data runs, there were no cases in which the maneuver was too difficult to be completed satisfactorily.

Pilot Rating of the FCMU Handling Characteristics

A summary of the pilot-rating values assigned by four of the five test subjects for the various maneuvers under the three test conditions is given in table 6. The values assigned by the other subject were not included because of several inconsistencies apparently resulting from unfamiliarity with the rating system. The subjects were encouraged to be decisive in their evaluations and not try to interpolate between rating values.

The ratings fall generally in the 3 and 4 categories that designate a system providing desired performance with a tolerable workload but with some unpleasant or annoying deficiencies. For a 3 rating, the system is considered satisfactory without improvement whereas a 4 rating indicates that improvements are warranted but not required. It is

notable that the four subjects were usually consistent to within 1 rating point for each case and that they usually made a distinction of no greater than 1 rating point between the various maneuvers and test conditions.

There is some indication that the degree of task difficulty influenced the system ratings slightly in that a few 2 ratings were assigned to the tasks considered the easiest. Likewise, there were several 4 ratings assigned to the task considered to be the most difficult.

Comparison of Performance Measurements by Groups and Individuals

Review of the average-total-maneuver-time measurements for the two subject groups in table 4 reveals that, for some cases, the two groups achieved quite similar results, whereas for others, they performed differently. In order to illustrate this point, a comparison for the case of the two ABS test conditions is shown in figure 13(a). This figure gives the mean time values for the two groups for each maneuver. The maneuvers are given in the sequence, from left to right, in which they were performed. The related values for a given group and test condition are connected by different lines to aid in interpreting the results. In this case, the differences between the two groups appear to be relatively minor. (Other aspects of this figure concerning EVA and IVA conditions will be discussed in a subsequent section.) In figure 13(b), which shows the comparison based on the VTS results, the differences between the two groups are fairly large, with the crewmen taking generally from 20 to 40 seconds longer to complete each maneuver than the instructors.

In order to gain better insight into some of these differences, the total performance time for the EVA pitch maneuver in the ABS and VTS is presented in figures 14(a) and (b), respectively, for each subject on a run-to-run basis. In this case all runs are given, including those (indicated by the solid symbols) that contained anomalies and were deleted in the previous averaged data. As an aid in interpreting these figures, the mean and standard deviations for each subject's data are shown at the right of each pilot.

The plots for the ABS show a fairly high degree of consistency for each subject with generally no more than 10 seconds difference between runs. In this case, there were no apparent anomalies and no significant differences between subjects. Also, the mean values for all subjects were within about ±20 percent of the average time, 73 seconds, for the group (denoted by the dashed horizontal line). By contrast, for the VTS tests, which were previously noted to be more difficult than the ABS tests, there were several anomalous runs for the crewmen but only one for both instructors. The mean value for the crewmen was about 50 percent greater than that for the instructors which, in turn, was only slightly greater than the group average for the ABS shown in figure 14(a).

The longer run times of the crewmen were found to closely correlate with high values of the mismatch parameter which indicates poor foot coordination and insufficient practice in the VTS. This correlation is illustrated in the plot given in figure 15 which shows the mismatch parameter values versus the relationship of the mismatch parameter to the corresponding total maneuver times from figure 14(b). The data points for the two instructors are clustered quite close to the origin, in the range of 5 to 10 percent mismatch, as compared with 10 to 20 percent for the crewmen.

It appears, therefore, from this discussion that the performance differences for the two groups can be explained on the basis of the relative ease of the task and the degree of piloting proficiency developed by each subject.

Comparison of Individual Performance Measurements for the ABS and VTS Tasks

The mean time for each subject to perform each of the EVA tasks in the VTS was compared with that in the ABS. This comparison was made to show the influence of changing from the easier ABS to the more difficult VTS and was determined on the basis of the following expression:

$$\text{Percentage change in total maneuver time} = \frac{\bar{T}_{VTS} - \bar{T}_{ABS}}{\bar{T}_{ABS}} 100$$

where $\bar{T}_{ABS}$ and $\bar{T}_{VTS}$ are each individual's mean total maneuver time values given in table 4(a) for the ABS and VTS, respectively. The results of this comparison for each of the comparable maneuvers are given in figure 16(a). Also included in this figure is each subject's average change for the four maneuvers involved in the comparison. This figure shows a fairly consistent trend from subject 1 to subject 5 in that subject 1 had relatively large increases in maneuver times whereas subject 5 had some decreases in maneuver times when going from the ABS to VTS. The other subjects had results which were between the two extremes.

Figure 16(b) is a crossplot of the results given in figure 16(a), with the data plotted from left to right in the sequence in which the maneuvers were performed. This crossplot reveals general reduction in the maneuver time in the VTS relative to the ABS in the sequence of the first three maneuvers for all the subjects. This is followed, however, by a generally large increase for the last maneuver.

The results shown in these two plots appear to be related to the factors of task difficulty and piloting proficiency as experienced in the simulator in the following manner. First, the maneuver-time change for the pitch maneuver (a moderately difficult task) by each subject, as shown in figure 16(a), is considered to be an indication of the relative

level of his pitot proficiency for the VTS at the beginning of the test. Second, the changes noted in the sequence of the first three maneuvers, as shown in figure 16(b), are the combined result of an improvement in proficiency due to adapting during the preceding maneuvers and of a change from moderately difficult tasks to an easier task. The subsequent increased time change for the last maneuver is considered to be primarily the result of the change from the easiest to the most difficult task. The fact that the percent change for each individual was not so great for this last maneuver as it was for the somewhat easier first maneuver is attributed to the warming-up or adaptation process accruing from the prior runs.

This interpretation is supported by the data for the mismatch parameter obtained from the VTS tests, as given in figures 17(a) and (b). The first plot shows the mean mismatch values for each of the subjects given in the sequence from left to right in which the maneuvers were performed. Also included in this plot are the combined mean values for the two instructors. These values were taken as reference values representative of fully proficient individuals. The fact that these reference values differed for each maneuver is attributed to differences in the combinations and total numbers of inputs required to perform the various maneuvers. The second plot shows the differences between each subject's values and the reference values. The two dashed lines correspond to an assumed reasonable tolerance band of ±3 percent difference from the average to allow for variation from person to person; this band is based on the spread in the values for the instructors. Values falling above this band (that is greater than 3 percent) are considered to represent excessive amounts of uncoordinated inputs attributed to insufficient practice or pilot proficiency. This plot indicates that all three crewmen generated a comparatively higher amount of uncoordinated control inputs for the first maneuver. However, for the subsequent maneuvers, the values for two of the crewmen fall within the designated tolerance band and those of the third subject approached this band. These trends are consistent with the adaptation process that was assumed to be involved.

It is interesting to note that in spite of this adaptation process evidenced in figures 16 and 17, there were no learning trends evident for any of the subjects on the run-to-run basis for each maneuver. This observation suggests that for a given number of runs the proficiency levels of the subjects in a particular simulator were influenced more favorably by performing several different types of maneuvers than by repeated performances of the same maneuver.

Comparison of Performance Measurements for the EVA and IVA Tasks

The primary differences between the EVA and IVA piloting tasks performed in the ABS were the quantity of visual cues with which the subject could judge his maneuvers and

the space available for maneuvering. As shown in figure 13(a), the average times for all subjects were reasonably close together for the pitch maneuver, in both EVA and IVA conditions. Reference to table 4(c) indicates that there was only a relatively small difference in the mean angular rates of the crewmen for these two conditions. It appears evident, therefore, that the differences in visual cues and maneuvering space had relatively little effect on the subjects' ability to perform the rotational maneuvers.

The translation maneuvers for the EVA conditions obviously required a longer time to complete than those for the IVA condition because of the greater distance traveled; that is, 13 meters (40 ft) as compared with about 5 meters (15 ft). However, although the distance was about $2\frac{1}{2}$ times as great for the EVA condition, the performance times were only about $1\frac{1}{2}$ times as long, as shown in figure 13(a). The discrepancy is explained with the aid of figure 18. This figure is a plot of the mean values of the maximum rates for all five subjects taken as a group for each of the three maneuvers performed in the EVA and IVA test conditions. It is evident that the subjects used higher rates in the EVA condition where they were less confined. Consequently, they were able to complete the tasks in a shorter time than would have been expected on the basis of extrapolating the IVA test results.

Comparison of Premission and Postmission Tests

One specific objective of the postmission simulation tests was to determine if the zero-gravity experiences of the two flight subjects had influenced the subjects to the point of altering their subsequent performances in the simulators. Figure 19 shows the comparison of the plots of the average total maneuver times in the ABS for the four maneuvers performed by subjects 1 and 2, both before and after they had conducted the in-flight tests. The averages for the two instructors are also given in this plot to indicate that the premission performances of the crewmen for the ABS were comparable to those of the instructors. Comparison of the premission data with those for the postmission tests indicates that both crewmen completed each of the maneuvers in noticeably shorter times.

These results suggest that experience with a new and unusual system gained solely in simulators tends to result in basically conservative performances (long times and slow rates) by the subjects. (This is probably due to the uncertainties of the simulated conditions.) But when provided with experience in the actual conditions, the subjects will modify their performance in the simulators to more representative levels.

Observations and Subjective Comments

The following discussions cover a range of specific aspects of the simulation study and are based on the observations of the investigators and on the comments of the crewmen, particularly the two that conducted the in-flight tests.

Training.- The training received by the crewmen on the ABS prior to the taking of the baseline data was considered adequate on the basis of the similarities between the ABS performance measurements of the crewmen and those of the instructors. The amount of training apparently was adequate, primarily because of the relative ease of the various tasks for this three-degree-of-freedom simulator. By contrast, the amount of crewman training on the VTS, which was only about one-half of that received on the ABS (see table 3), appeared to be adequate only for developing the basic skills of controlling the FCMU with six-degree-of-freedom motion. Because of the greater degree of task difficulty in this simulator, the training was not sufficient for developing and maintaining a relatively high degree of piloting proficiency in that particular simulator. Based on the trends evident in the baseline data of the crewmen, it is estimated that an additional 10 to 20 hours of time would have been adequate for each of the crewmen to have fully developed their piloting proficiency on the VTS. However, it is doubtful that additional ground training would have significantly improved piloting proficiency for the in-flight tests because of the long delays between final ground training and the in-flight tests.

After completion of their space missions, both flight subjects indicated that they had sufficient ground training on both simulators to permit them to perform the in-flight tests satisfactorily, although subject 1 stated that he would have liked to have had more time on the VTS to improve his proficiency. He specifically noted that a few short sessions with a break of several hours in between were preferable to a long continuous session. Subject 2 noted that the VTS seemed to have "a personality of its own," due more to the limitations and artifacts of the simulator than to the subject's workload of controlling six-degree-of-freedom motion; consequently, considerable time was spent in each session adapting to the simulator. Subject 3 commented in a similar manner as did subject 2 but noted that the skill he had developed during his first session had "stuck with him" during a period of about a year until his second session.

Body support and restraint systems.- In general, the subjects reported no significant difficulty with the body support and restraint systems for both simulators and considered them to be comfortable for the test period which lasted up to 2 hours, and longer, without a break. However, the flight subjects reported that the simulators failed to duplicate the zero-gravity effects that influenced the effectiveness of the restraint system and the subjects' ability to make desired control inputs. Both subjects experienced severe difficulties during the in-flight tests with the original body harness because of the fact that the body was not adequately secured in the FCMU seat and was free to bend at the waist. Subject 1 noted that the simulators actually represented a much more rigid restraint system, and he strongly recommended the incorporation of some rigidizing scheme into the flight equipment. Such a scheme was employed by subject 2 for most of his in-flight tests, and he found it to be very effective.

For the VTS with the subjects seated in a near upright position, the subject's weight kept his body firmly on the seat and his feet on the pedals and prevented them from shifting whenever he made control inputs. For the ABS with the subject reclining on his side, his body was prevented from shifting away from the seat primarily because of friction between his body and the support system of the simulator. Both situations contributed a sense of firmness or rigidity that was not present in the weightless conditions.

Based on these findings, it was concluded that the body must be firmly restrained for the weightless conditions by an adequate harness system and that in this case the differences between the simulated and actual weightless conditions should be relatively unimportant.

Influence of body orientation.- The horizontal orientation of the body for the ABS presented no significant problems to the subjects and generally was considered to be a reasonable arrangement for the three-degree-of-freedom simulator. In the case of the VTS, however, the off-vertical orientation of the operator's body presented a sensory problem in which all the subjects had a tendency to aline the simulated horizon perpendicular to the gravity vector, as is the case for the actual horizon. The sketch of figure 20 shows the subject as he is seated on the FCMU mockup in the VTS; he is inclined about 20° backward to improve the seat comfort on the FCMU. The visual scene is shown oriented so that the reference Z-axis of the FCMU is perpendicular to the simulated Earth horizon. In this case, the simulated horizon in front of the subject is elevated about 40° above the real horizon because of the 20° inclination of back rest and the additional 20° inclination of the reference Z-axis with respect to the seat. The subjects, when asked to maneuver the FCMU into this attitude in the simulator, quite often unconsciously allowed the simulated horizon to slowly drift and become perpendicular to the gravity vector. This tendency often resulted in the subjects misjudging the attitude of the FCMU and generating large unwanted translation drift rates due to the misalinement. This problem complicated the VTS task and required considerable attention on the part of the subject to overcome.

A solution to this problem is considered to be reorientation of the subject to a horizontal position either directly on his back or on his side. This latter position appears to be a more reasonable arrangement inasmuch as it worked quite satisfactorily for the ABS.

Acceptability of simulators.- As discussed previously, all maneuvers were considered to be more difficult to perform in the VTS than the ABS. This was due primarily to the poorer quality of the visual cues of the VTS as compared with the ABS, as well as to the additional degree-of-freedom motion and to the body orientation problem just discussed. The general consensus of the test subjects, based on the premission tests, was that the in-flight maneuvers inside the OWS should be more difficult than those in the ABS

but not as difficult as those in the VTS. The postmission comments of the two flight subjects confirmed this opinion.

The poor quality of the visual cues in the VTS was due primarily to the use of some out-dated television equipment that was the only readily available system at the time the simulator was developed. Its use resulted in the inability of the subjects to detect and distinguish small motions and to judge their position relative to the target spacecraft. It appears that a more realistic duplication of the maneuvering tasks could be achieved by use of up-to-date visual projection equipment which has the benefit of significant technical improvements over the system used in the VTS.

The audio cues produced by the FCMU thrusters firing were found to be very helpful by the subjects. The flight subjects indicated that the sounds in the ABS were almost the same as those in the OWS and recommended that such sounds or appropriate substituted sounds be used in all other simulators where applicable. These sounds had not been provided in the VTS, and the subjects commented that this was an undesirable omission.

Although the performance measurements differed between subjects, as discussed previously, there did not appear to be any significant differences in the piloting techniques employed by each subject for the same maneuver performed in either simulator. There was, however, a marked difference in the evaluation of the fidelity of the simulators by the two flight subjects. Subject 1 took the position that the tasks provided by the ABS were misleading because they were unrealistically easy whereas those provided by the VTS, although somewhat more difficult than the actual case, were far more realistic. On the other hand, although subject 2 also found the ABS to be easier than the actual case, he considered the ABS tasks to be fairly representative and found that the differences were essentially what he had expected them to be. Furthermore, he considered the VTS to be seriously lacking in realism because of the overall poor quality and minimal number of visual cues.

In defense of these two harshly opposed opinions, it should be noted that each subject was relating to a different set of conditions for the in-flight tests. In the first case, subject 1 used only the original flight restraint harness which was found to be deficient and was not truly represented in the simulators. Subject 2, however, completed most of his tests with the modified harness which was found to be very much superior to the original and closely matched the conditions of the simulators.

Both subjects did concur, however, that the simulators were useful for training. They also commented on the desirability of a simulation technique combining the major attributes of the two simulators; that is, providing six-degree-of-freedom motion within a full-scale three-dimensional mockup of the OWS.

SUMMARY COMMENTARY

The following is a summary commentary on the results of this simulation study:

1. All maneuvers were performed successfully by all subjects but not necessarily with the same degree of precision or consistency by each subject. Differences in the performances of the various subjects in the simulators were attributed primarily to differences in the amount of time devoted to practice prior to the tests and to improvement in pilot proficiency during the tests. The crewmen test subjects had received sufficient training to develop the basic control coordination and piloting skills required to operate the FCMU system in the simulators but apparently had not fully developed their proficiency because of the press of their other mission commitments and lack of adequate practice time. Their proficiency was found to improve more rapidly by performing many tasks a few times each rather than by repeatedly performing a few tasks.

2. The maneuvers selected for this experiment were rather limited, and somewhat artificial in nature, but did provide the subjects with piloting tasks having a wide range of difficulty when performed in both simulators. Piloting tasks in the air-bearing simulator (ABS) were considered to be relatively easy and were performed in a similar manner by all subjects. The corresponding maneuvers in the visual-task simulator (VTS) were more difficult, and the subjects with the greater experience demonstrated better control coordination and completed the tasks more quickly. The basic piloting techniques employed by all subjects were generally similar for both simulators, although task difficulty was different.

3. Translation rates, considered to be desirable or comfortable by the test subjects, were higher for the simulated EVA condition than for the IVA case. However, the corresponding angular rates were essentially the same for both cases.

4. Based on the flight subjects' experiences in actual zero gravity, there were notable differences between the ground-based and in-flight test conditions; that is, body restraint problems were much more severe in zero gravity and had a significant influence on the handling qualities of the FCMU, vertical orientation of the subject in the VTS caused the gravity vector to influence his judgment of pitch attitude relative to the simulated target spacecraft and horizon (this effect was not noted for the horizontal orientation used in the ABS), and the piloting tasks in the OWS were more difficult than those in the ABS but were easier than those in the VTS.

5. Significant differences were found between the premission and postmission performances of the two flight subjects in the ABS with the premission sessions being more conservative in terms of total maneuvering time and maximum rates.

6. Both simulators proved useful in training and the collection of baseline data for operation of the FCMU system. The use of more than one zero-gravity simulator for

future maneuvering-system studies is recommended because of the limitations and artifacts of zero-gravity simulation techniques, in general, and also because of the strong differences in personal preference expressed by the two flight subjects toward the two techniques employed in this experiment.

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APPENDIX A

DESCRIPTION OF THE FCMU ZERO-GRAVITY SIMULATORS

The decision to use two different types of zero-gravity simulation techniques for evaluation of the FCMU was based primarily on the recognition that all ground-based simulators have limitations and artifacts (features detracting from the subject's sense of realism) that reduce the fidelity of zero-gravity conditions being produced. The extent to which these undesirable factors influence the simulation fidelity was unknown, due to lack of prior knowledge and experience. Consequently, the use of two simulators, having different types of limitations and artifacts for the same application, appeared to offer the opportunity not only to obtain a more comprehensive evaluation of the FCMU itself but also to gain some insight as to the significance of some of the undesirable factors.

The following discussions provide descriptions of the air-bearing simulator (ABS) and the visual-task simulator (VTS) and identify those features of each that are considered to be attributes and those that are deficiencies.

Air-Bearing Simulator

The air-bearing simulator consisted primarily of the engineering development model of the FCMU complete with operating thrusters and gas-supply system, an air-bearing system that supported the FCMU and the test subject, and a very smooth and level plastic floor surface over which the air-bearing system moved with very low friction. Some of the details are shown in figures 4 and 5 and some of the operating characteristics are listed in table 7. The simulation area, including the floor surface and a surrounding work area, was enclosed within a nearly airtight room. This room was kept at a slightly elevated atmospheric pressure by a filtered ventilating fan so as to minimize the infiltration and circulation of dirt and dust particles that seriously interfered with proper operation of the low-clearance air bearings. An entrance room in which street clothing and shoes were exchanged for special dust-free clothing was used as an additional barrier to foreign matter. The simulation room was made light-tight so that lighting conditions could be controlled.

This simulator was set up to provide two different test conditions: the first, corresponding to the intravehicular activities (IVA) within the Skylab orbital workshop (OWS) as shown in figure 4 and, the second, corresponding to the extravehicular activities (EVA) carried out in the other simulator, as shown in figure 5. Full-scale replicas of the most prominent features were used in these two setups. In the case of the IVA conditions, the replicas were located within a 2.67-meter-high by 7-meter-diameter shell structure representing the interior walls of the spacecraft. The features provided in this mockup were located in exactly the same positions as those that were in the area of the workshop in which the in-flight tests were performed. In the case of the EVA conditions, a full-

size mockup of an orbiting satellite was used as the primary source of visual cues. As shown in figure 5, the mockup was positioned at one end of the air-bearing floor within a partial enclosure, painted black on the interior. This enclosure was used to minimize reflection of the light used to illuminate the target into the rest of the simulator area. The target enclosure was large enough to permit the subject to "fly" inside and reach the target. Due to the smooth reflective quality of the air-bearing surface, the subject was able to see a reflection of the target in the floor surface; however, this reflection appeared to have no significant influence on the subject's perception of his motion relative to the real target. A vertical structural member of the enclosure immediately behind the target was used by the subject lying on his side as a "horizontal" reference in lieu of a simulated Earth horizon. All lights other than those used to illuminate the target were turned off so as to eliminate or minimize all visual cues other than the target spacecraft itself.

The air-bearing support shown in figure 4 was used to provide three-degree-of-freedom motion in the pitch plane of the FCMU. That is to say, the subject had direct control of motion along the fore-aft and up-down axes and about the lateral or pitch axis by use of the thrusters on the FCMU. Roll, yaw, and lateral translation motions were restricted by the support system and floor reactions. A second support system, somewhat similar to the one shown but with the FCMU and subject mounted with him lying on his back, was also used to provide freedom of motion in the roll plane which included the up-down and lateral or sideways motions. Pitch, fore-aft, and yaw motions were restrained for this arrangement.

The favorable features of the air-bearing simulator are as follows:

(1) The subject operated an actual duplicate of the maneuvering unit equipped with active thrusters. This provided the subject with the feel and sounds of the real unit.

(2) The test operator experienced actual motion as the result of the thrusters firing or contact with surrounding objects. This provided him with a feel for the forces and accelerations involved.

(3) The simulator provided full-scale mockups of the objects, either intravehicular or extravehicular, which created realistic visual cues when used in conjunction with the appropriate lighting.

(4) Inasmuch as the gravity vector was acting essentially perpendicular to the plane of motion for the system, the direct influences of gravity on subjects proprioceptive cues for judgment of body attitude in that plane were circumvented.

The following features and characteristics of the air-bearing simulator were considered to introduce possible detrimental effects:

(1) The motion of the system was restricted to only three degrees of freedom; that is, to planar motion. The direct consequence was that the operator was prevented from exercising command over all six-axes control and from performing maneuvers that

change planes of motion. Furthermore, he did not have to contend with the influences of control cross coupling resulting from mismatched control inputs, misalined thrusters, and inertial interactions.

(2) The range available for maneuvering was limited to less than about 15 meters. Although adequate for most IVA and a few EVA type maneuvers, this range was not considered sufficient for many other forms of EVA operations.

(3) The subjects' legs and feet had to be supported so that they were free to operate the controls without their weight influencing the operating force levels. Also, the gravity vector prevented the simulation of the body motions in weightless conditions that were critical with respect to the harness-restraint system.

(4) The influences of the orbital velocity on the trajectory of the maneuvering unit could not be produced.

(5) The maneuvering unit was subject to very small but discernible forces produced by minute deviations in the levelness of the floor surface, drag of the air bearings across the floor, and drag produced by the air moving relative to the complete unit. This latter factor was particularly noticeable if the air was being circulated in the room for cooling and ventilating purposes.

Visual-Task Simulator

The visual-task simulator was referred to in terms of the visual task inasmuch as there was no physical motion of the subject involved. That is to say, the visual display was the only source of motion information available to the subject. The visual scene from which the subject derived the information concerning the simulated motion is depicted in figure 8. The subject was seated on a nonoperating mockup of the FCMU with electrical switches in the foot pedals for the control signal inputs to the computer. The scene, projected on the inside of a 6.1-meter-diameter spherical screen which completely surrounded the test subject, consisted of a projected image of a small spacecraft corresponding to a typical unmanned satellite and the shadow from a single small light depicting the sky and the Earth horizon.

The image of the target spacecraft was projected by a television system which used a small model moving in front of the camera for the purpose of creating most of the visual effects of motion of the FCMU relative to the spacecraft. The motion of the line of sight from the FCMU to the target was produced by servo-driven mirrors at the projector which moved the image to the appropriate position on the screen. A servo-driven hemispherical mask partially surrounded the small light near the center of the spherical screen to create the shadow representing the dark sky. The dimly lit portion of the sphere represented the Earth surface, and the edge of the shadow corresponded to the horizon. Some of the details can be seen in figures 6 and 7.

APPENDIX A

This simulator was programed to represent the six-degree-of-freedom motion of a rigid FCMU system in orbit around the Earth at an altitude of about 320 kilometers and included the orbital velocity effects on the motion. The FCMU was assumed to be in a synchronous orbit with the target spacecraft for most conditions at the start of the runs. The attitudes of the FCMU, and its range and range rates relative to the target spacecraft, were unlimited in the computer program. However, the physical capabilities of the television projection system for the spacecraft limited the practical range for displaying relative motions to a minimum of about 3 meters from the center of gravity of the target to a maximum of about 50 meters. Beyond this point, the image remained essentially a fuzzy spot of light useful in determining the location of the target but not the relative range or range rate. The equipment used for this simulator was not of recent vintage; as a result, the qualities of the visual display in terms of image brightness and resolution were not up to present-day standards. A list of some operating characteristics is given in table 8.

The favorable aspects of the visual-task simulator were considered to be:

(1) The test operator was able to perform EVA type maneuvering with complete six degrees of freedom. Consequently, he was able to exercise all control inputs and experience the various forms of cross coupling. He was able to perform any desired changes in direction of his trajectory and attitude.

(2) The influences of the orbital velocity on the trajectory of the maneuvering unit were included in the simulation and could be deleted readily so as to permit an evaluation of their significance.

(3) A moderate maneuvering range of about 70 meters from the target spacecraft along with unlimited attitude changes permitted the performance of many EVA type maneuvers. This range could be extended indefinitely although the visual cues would not have changed correspondingly. The velocity limits of the visual system were well in excess of the velocities normally expected to be utilized for maneuvering.

(4) The distant visual cue derived from reference to the Earth's horizon provided a convenient reference for attitude and attitude rates when the target spacecraft was not within view.

Those unfavorable aspects of the visual-task simulator were as follows:

(1) The test subject was unable to make physical contact with the target vehicle and was not exposed to acceleration and audio cues associated with the thruster firings.

(2) The visual scene was a two-dimensional image which was subjected to significant distortion at ranges of less than about 3 meters. The projected images were of relatively low resolution, brightness, and contrast in comparison to the real-life situation. Furthermore, the visual scene lacked additional features such as Sun, Moon, stars, and Earth surface details that could be present in a typical EVA situation. These visual deficiencies

imposed some additional workload on the pilot by requiring him to devote a greater share of his attention to interpretation of the somewhat limited visual cues that were available.

Considerable improvements could have been achieved with up-to-date equipment, but schedule and cost considerations had prevented replacement of the equipment at the time the tests were undertaken.

(3) The visual system was not capable of producing a visual environment equivalent to that of an IVA situation with a large multitude of close-range objects, a situation in which visual depth perception is a particularly significant judgment factor for the operator.

APPENDIX B

DESCRIPTION OF TEST MANEUVERS

The following are descriptions of each of the test maneuvers given in the sequence in which they were performed.

Pitch-Attitude Change and Hold

Starting from initial conditions of essentially zero rotation and translation, the operator's primary task was to perform a 90° change in pitch attitude using whatever rate was considered desirable or comfortable. Upon reaching the 90° position, the operator was to hold that position for a period of at least 10 seconds during which time he held his estimated pitch attitude and rate within about $\pm 10^{\circ}$ and $\pm 1^{\circ}$ per second, respectively. When these were firmly established, he then was to repeat the maneuver in the opposite direction. Throughout the complete maneuver, the operator's secondary tasks were to maintain the roll and yaw attitudes and rates within the same limits as pitch and also to maintain his position within 1 meter of his starting position.

Roll- and Yaw-Attitude Change and Hold

The roll and yaw maneuvers were the same as for pitch except that they were performed separately about the roll and yaw axes.

Single-Axis Translation

Starting from initial conditions of essentially zero motion with the thrust axis alined with the target position, the operator's primary task was to perform a translation maneuver directly to the target position using whatever rate was considered desirable or comfortable. Upon reaching the target position, the operator was to maintain that position for a period of at least 10 seconds, during which time he was to hold his translational position and rates within about ± 0.3 and ± 0.03 meter per second. Throughout the complete maneuver, the operator's secondary tasks were to maintain the pitch, roll, and yaw attitudes within the previously prescribed limits, except as was required to control spatial-drift rates.

Double-Axis Translation

Starting from the zero-motion initial condition with the thrust axis pitch about 10° down from the target position, the operator's primary tasks were to aline the thrust axis with the target and initiate translation toward it at the desired rate, then to pitch 90° down so as to be able to make cross-range corrections, and finally to complete the maneuver by

grasping the target and braking his translational and rotational rates with his arms and hands. (In the case of the VTS where direct contact with the target was not possible, the run was merely terminated at the appropriate distance with no braking action.) The operator's secondary tasks were to maintain the roll and yaw attitudes within the specified limits. In this case, the FCMU was not used to alter the translational rate as the target was approached.

Dogleg Translation

Starting from the zero-motion initial conditions at some distance from the target with the line of sight to the target pitched up approximately 45^{o} from down-thrusting axis (positive reference Z-axis), the operator's primary tasks were to initiate a translation in the direction of the thrust axis, then pitch down about 30^{o} so as to be able to thrust toward the target by firing the up-direction thrusters. The upward thrusts, applied at intervals, redirected the FCMU to the target with a somewhat reduced translational rate. The operator terminated the maneuver as he grasped the target. The secondary tasks were similar to those previously defined for the other maneuvers.

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TABLE 1.- FOOT-CONTROL LOGIC FOR FCMU

Commanded acceleration		Control input		Active thruster nozzle	
Axis	Direction	Left	Right	Left	Right
Pitch	Up	Toe up	Toe up	Aft	Aft
	Down	Toe down	Toe down	Fore	Fore
Yaw	Right	Toe up	Toe down	Aft	Fore
	Left	Toe down	Toe up	Fore	Aft
Translation	Up	Foot up	Foot up	Bottom	Bottom
	Down	Foot down	Foot down	Top	Top
Roll	Right	Foot up	Foot down	Bottom	Top
	Left	Foot down	Foot up	Top	Bottom

TABLE 2.- CALCULATED CHARACTERISTICS[a] OF FCMU SYSTEM

	SI Units	U.S. Customary Units
Weight	139 kg	307 lb
Principal moments of inertia:		
Roll	47 kg-m^2	35 slug-ft^2
Pitch	43 kg-m^2	32 slug-ft^2
Yaw	4.9 kg-m^2	3.6 slug-ft^2
Thruster size:		
Pitch-yaw	136.1 g	0.3 lb
Translation-roll	453.6 g	1.0 lb
Inclination of principal axes from reference axes	7^o	7^o
Control accelerations:		
Roll	3.0 deg/sec^2	3.0 deg/sec^2
Pitch	3.8 deg/sec^2	3.8 deg/sec^2
Yaw	9.4 deg/sec^2	9.4 deg/sec^2
Translation (Z-axis)	6.2 cm/sec^2	0.20 ft/sec^2

[a] Typical values for shirt-sleeve conditions.

TABLE 3.- SUMMARY OF SIMULATION TRAINING HOURS PRIOR TO BASELINE DATA RUNS[a]

Subject	Identification	Training hours		Total hours
		Air-bearing simulator (b)	Visual-task simulator	
1	Prime crewman	18	12	30
2	Prime crewman	20	11	31
3	Backup crewman	14	7	21
4	Instructor	>60	>60	>120
5	Instructor	>120	>140	>260

[a] The baseline data runs provided additional simulator time of about 4 and 2 hours on the ABS and VTS, respectively, for each of the crewmen.

[b] Includes total time in the air-bearing training simulator located at NASA Lyndon B. Johnson Space Center.

TABLE 4.- SUMMARY OF MEAN VALUES

(a) Total maneuvering times

Maneuver	Subject	Times		
		IVA – ABS, sec	EVA – ABS, sec	EVA – VTS, sec
Pitch	1	73 ± 5	65 ± 2	115 ± 15
	2	83 ± 4	74 ± 4	111 ± 3
	3	75 ± 8	79 ± 6	107 ± 3
	4	80 ± 7	75 ± 4	81 ± 5
	5	64 ± 8	72 ± 4	71 ± 5
	Crewmen	77	73	111
	Instructors	72	73	76
Roll	1	75 ± 8	-------	153 ± 14
	2	78 ± 6	-------	87 ± 6
	3	65 ± 3	-------	130 ± 10
	4	65 ± 2	-------	87 ± 6
	5	64 ± 3	-------	78 ± 5
	Crewmen	73	-------	123
	Instructors	65	-------	83
Yaw	1	------	-------	84 ± 15
	2	------	-------	87 ± 4
	3	------	-------	100 ± 12
	4	------	-------	88 ± 6
	5	------	-------	60 ± 7
	Crewmen	------	-------	90
	Instructors	------	-------	74
Single axis	1	58 ± 5	85 ± 13	136 ± 16
	2	44 ± 3	76 ± 8	74 ± 6
	3	54 ± 2	106 ± 10	114 ± 12
	4	57 ± 4	88 ± 7	102 ± 15
	5	47 ± 2	94 ± 10	88 ± 13
	Crewmen	52	89	108
	Instructors	52	91	95
Double axis	1	52 ± 7	84 ± 12	92 ± 10
	2	45 ± 5	64 ± 5	65 ± 7
	3	49 ± 3	71 ± 7	76 ± 12
	4	45 ± 5	63 ± 6	58 ± 4
	5	45 ± 3	78 ± 7	50 ± 5
	Crewmen	49	73	78
	Instructors	45	71	54
Dogleg	1	61 ± 3	84 ± 10	136 ± 8
	2	37 ± 3	59 ± 3	81 ± 12
	3	43 ± 11	71 ± 8	65 ± 10
	4	50 ± 5	71 ± 7	103 ± 11
	5	50 ± 4	70 ± 7	60 ± 5
	Crewmen	47	71	94
	Instructors	50	70	82

TABLE 4.- Continued

(b) Impulse

Maneuver	Subject	Impulse		
		IVA – ABS, N-sec	EVA – ABS, N-sec	EVA – VTS, N-sec
Pitch	1	23 ± 3	39 ± 8	20 ± 4
	2	25 ± 9	30 ± 11	27 ± 9
	3	34 ± 7	24 ± 7	15 ± 2
	4	29 ± 9	25 ± 3	23 ± 5
	5	34 ± 6	26 ± 5	29 ± 5
	Crewmen	28	31	21
	Instructors	31	26	26
Roll	1	57 ± 9	-------	48 ± 2
	2	49 ± 12	-------	46 ± 9
	3	83 ± 18	-------	37 ± 3
	4	74 ± 13	-------	70 ± 13
	5	64 ± 12	-------	48 ± 5
	Crewmen	63	-------	44
	Instructors	69	-------	59
Yaw	1	------	-------	35 ± 7
	2	------	-------	41 ± 13
	3	------	-------	25 ± 5
	4	------	-------	25 ± 7
	5	------	-------	29 ± 5
	Crewmen	------	-------	34
	Instructors	------	-------	27
Single axis	1	28 ± 6	74 ± 15	65 ± 12
	2	50 ± 5	102 ± 9	82 ± 9
	3	47 ± 8	89 ± 17	57 ± 5
	4	44 ± 10	90 ± 14	61 ± 11
	5	48 ± 6	83 ± 17	65 ± 15
	Crewmen	41	89	69
	Instructors	46	87	63
Double axis	1	35 ± 5	56 ± 6	37 ± 8
	2	49 ± 13	53 ± 5	52 ± 9
	3	51 ± 7	58 ± 7	46 ± 9
	4	44 ± 11	72 ± 16	61 ± 11
	5	41 ± 7	55 ± 16	66 ± 15
	Crewmen	45	56	45
	Instructors	43	64	63
Dogleg	1	46 ± 3	102 ± 15	82 ± 14
	2	97 ± 9	146 ± 13	138 ± 16
	3	93 ± 13	129 ± 21	131 ± 21
	4	86 ± 11	121 ± 25	97 ± 17
	5	95 ± 12	135 ± 24	115 ± 10
	Crewmen	79	125	117
	Instructors	91	128	106

TABLE 4.- Concluded

(c) Translational rates

Maneuver	Subject	Translational rates		
		IVA – ABS, deg/sec	EVA – ABS, deg/sec	EVA – VTS, deg/sec
Pitch	1	3.9 ± 0.6	5.5 ± 0.7	2.5 ± 0.4
	2	3.4 ± .6	4.9 ± .7	3.2 ± .4
	3	4.1 ± .7	4 ± .8	2.5 ± .2
	4	3.6 ± .6	4 ± .5	3.8 ± .5
	5	5.0 ± 1.0	4.3 ± 1.2	4.4 ± .6
	Crewmen	3.8	4.8	2.7
	Instructors	4.3	4.2	4.1
Roll	1	3.9 ± 1.0	---	2.5 ± 0.4
	2	4.2 ± .8	---	5.8 ± 1.0
	3	5.7 ± .5	---	2.3 ± .3
	4	4.8 ± .4	---	4.1 ± .6
	5	5.1 ± .6	---	3.7 ± .4
	Crewmen	4.6	---	3.5
	Instructors	5.0	---	3.9
Yaw	1	---	---	6.1 ± 2.5
	2	---	---	5.1 ± .8
	3	---	---	3.9 ± 1.4
	4	---	---	4.6 ± 1.5
	5	---	---	6.6 ± 1.5
	Crewmen	---	---	5.0
	Instructors	---	---	5.6

Maneuver	Subject	Translational rates		
		IVA – ABS, m/sec	EVA – ABS, m/sec	EVA – VTS, m/sec
Single axis	1	0.09 ± 0.01	0.19 ± 0.03	0.12 ± 0.02
	2	.14 ± .01	.27 ± .01	.26 ± .02
	3	.13 ± .01	.18 ± .02	.16 ± .02
	4	.10 ± .01	.17 ± .01	.17 ± .03
	5	.12 ± .02	.19 ± .04	.17 ± .03
	Crewmen	.12	.21	.18
	Instructors	.11	.18	.17
Double axis	1	0.10 ± 0.01	0.17 ± 0.03	0.13 ± 0.02
	2	.14 ± .01	.21 ± .01	.16 ± .03
	3	.14 ± .02	.20 ± .03	.16 ± .03
	4	.13 ± .02	.19 ± .02	.20 ± .02
	5	.13 ± .02	.20 ± .02	.24 ± .04
	Crewmen	.13	.19	.15
	Instructors	.13	.19	.23
Dogleg	1	0.10 ± 0.01	0.21 ± 0.04	0.11 ± 0.02
	2	.16 ± .01	.25 ± .01	.12 ± .01
	3	.15 ± .01	.24 ± .01	.30 ± .02
	4	.14 ± .02	.20 ± .01	.20 ± .01
	5	.17 ± .01	.24 ± .03	.25 ± .04
	Crewmen	.14	.23	.18
	Instructors	.16	.22	.22

TABLE 5.- SUMMARY OF PILOTING-TASK DIFFICULTY

Rating	Maneuver		
	IVA – ABS	EVA – ABS	EVA – VTS
Easy	Double axis Single axis	Double axis Single axis Pitch	Double axis
Moderate	Pitch Dogleg	Dogleg	Single axis Pitch Yaw Roll
Difficult	----------	----------	Dogleg

TABLE 6.- PILOT RATINGS[a] FOR SIMULATION TEST CONDITIONS

Maneuver	Rating		
	IVA – ABS	EVA – ABS	EVA – VTS
Pitch	3, 3, 3, 3	3, 3, 3, 4	3 to 4, 3, 3, 3
Roll	3, 3, 3, 3	--------	4, 3, 4, 4
Yaw	--------	--------	3, 3, 4, 3
Single axis	3, 3, 3, 3	4, 3, 4, 4	4, 2, 4, 3
Double axis	3, 3, 3, 3	3, 3, 2, 2	3, 3, 3, 3
Dogleg	3, 3, 4, 4	3, 3, 3, 3	4, 3, 4, 4

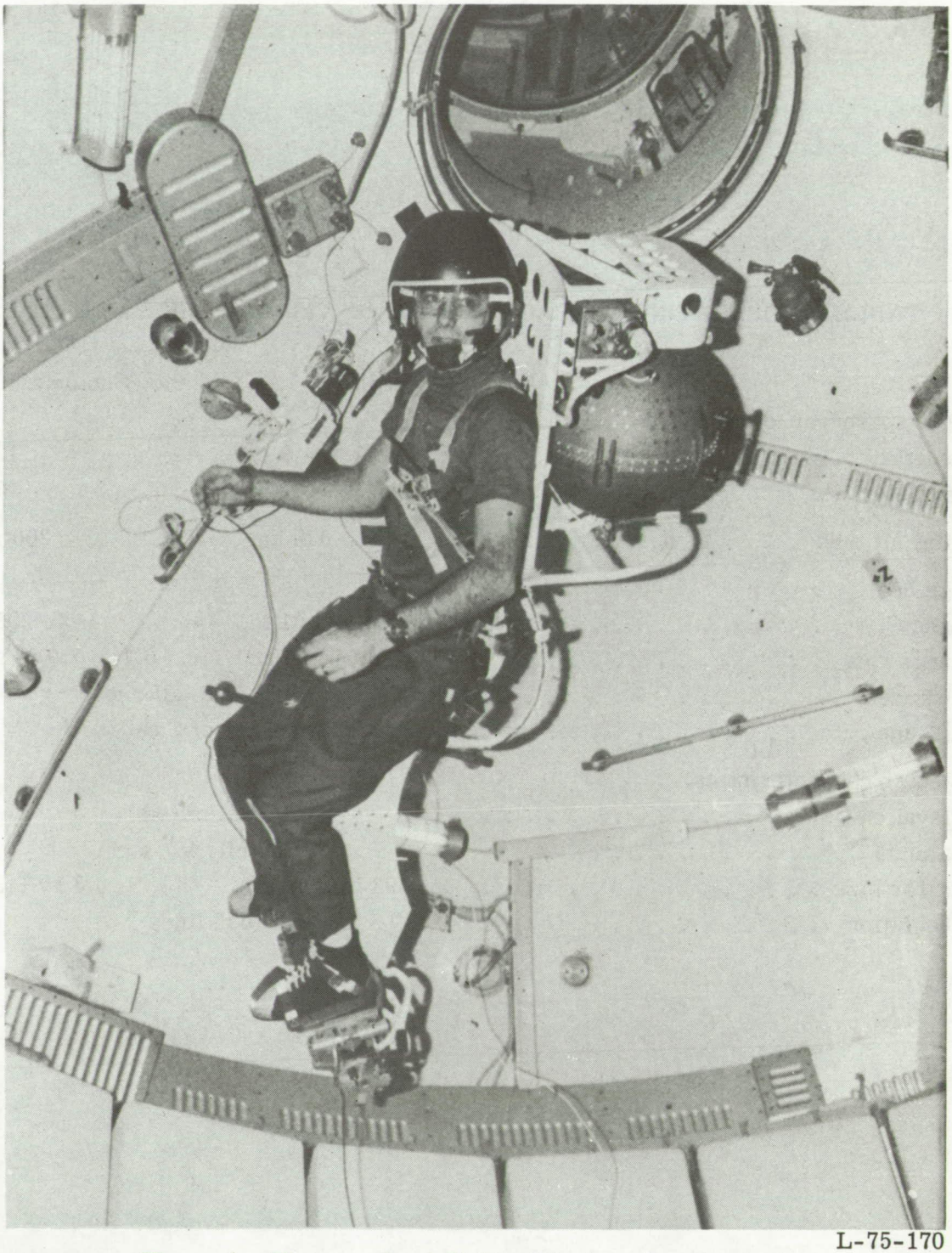
[a] Individual ratings assigned by four of the five subjects. Those of the other subject were not included due to several inconsistencies apparently resulting from unfamiliarity with the rating system.

TABLE 7.- OPERATING CHARACTERISTICS OF AIR-BEARING SIMULATOR

	SI Units	U.S. Customary Units
Maneuvering surface:		
Area	112 m^2	1200 ft^2
Maximum length	15 m	50 ft
Maximum width	9 m	30 ft
Surface deviations:		
In 1.5 m (5 ft) distance	0.010 cm	0.004 in.
In 15 m (50 ft) distance	0.038 cm	0.015 in.
Weight of FCMU mockup	84 kg	185 lb
Total weight including subject	154 kg	340 lb
Typical operating time using backpack gas supply system	30 to 60 min	
Thruster accelerations:		
Pitch	4 deg/sec^2	4 deg/sec^2
Roll	5 deg/sec^2	5 deg/sec^2
Translation	6 cm/sec^2	0.2 ft/sec^2
Typical extraneous accelerations:		
Surface deviations (slope)	0.082 cm/sec^2	0.0027 ft/sec^2
Bearing friction (viscous) at 15 cm/sec	0.039 cm/sec^2	0.0013 ft/sec^2
Air drag at maximum translation at 15 cm/sec	0.200 cm/sec^2	0.0063 ft/sec^2

TABLE 8.- OPERATING CHARACTERISTICS OF VISUAL-TASK SIMULATOR

	SI Units	U.S. Customary Units
Target spacecraft dimensions:		
Length	4.0 m	13 ft
Diameter	0.9 m	3 ft
Orbital altitude	370 km	200 nm
Range bed:		
Range	4 to 61 m	14 to 200 ft
Range rate	0.03 to 0.61 m/sec	0.1 to 2.0 ft/sec
Attitude	Unlimited, all axes	
Attitude rate	In excess of 1 rad/sec	
Projector characteristics:		
Elevation	Unlimited	
Azimuth	30^{o} left, 45^{o} right	
Raster size	1.93 by 1.93 m	6.3 by 6.3 ft
Resolution	675 lines	



L-75-170

Figure 1.- Photograph of flight subject performing test maneuvers in the Skylab orbital workshop.

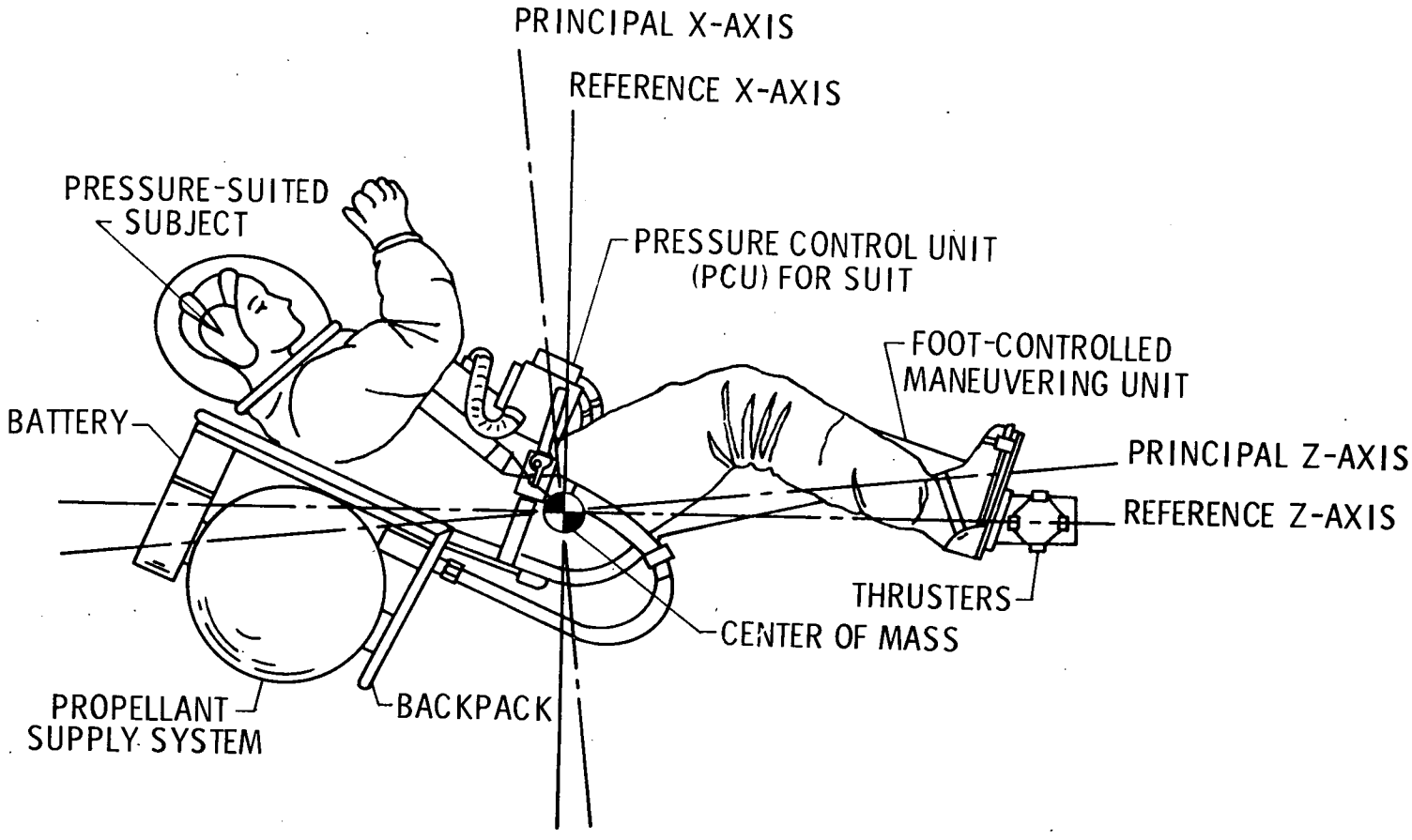


Figure 2.- Sketch of foot-controlled maneuvering unit system for the pressure-suited condition.

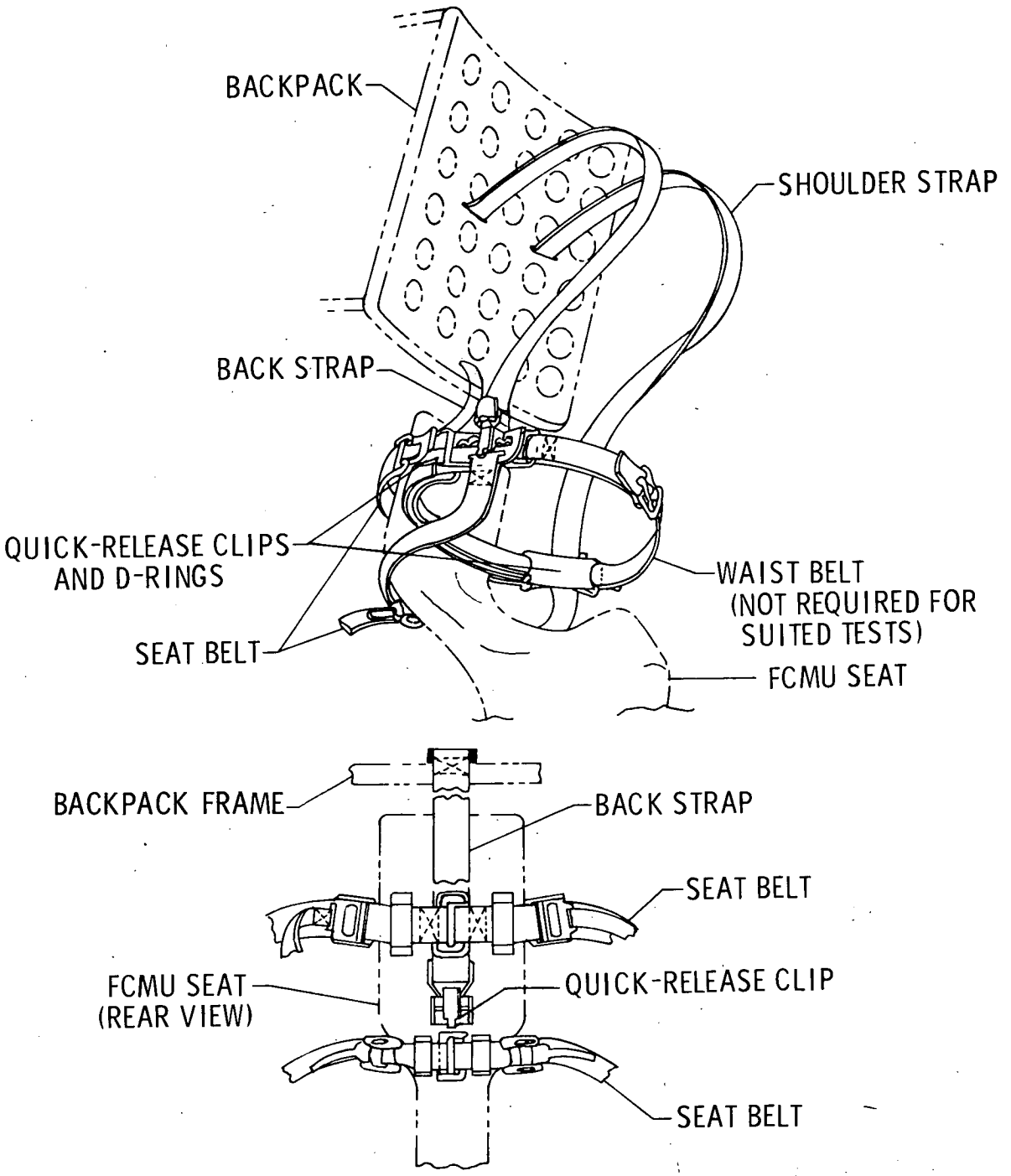
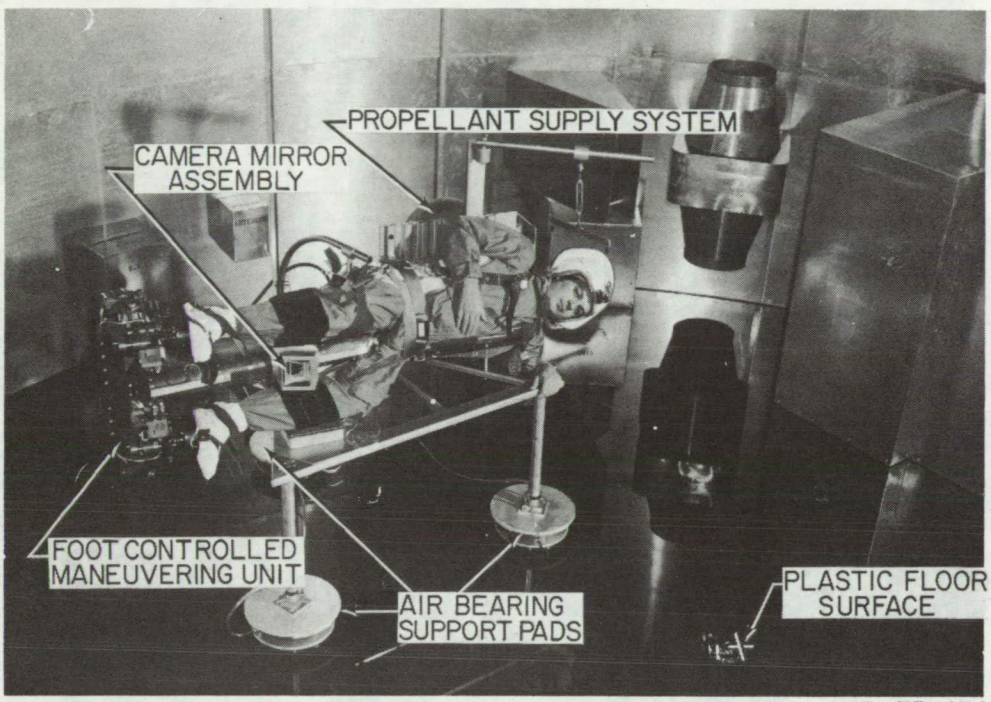
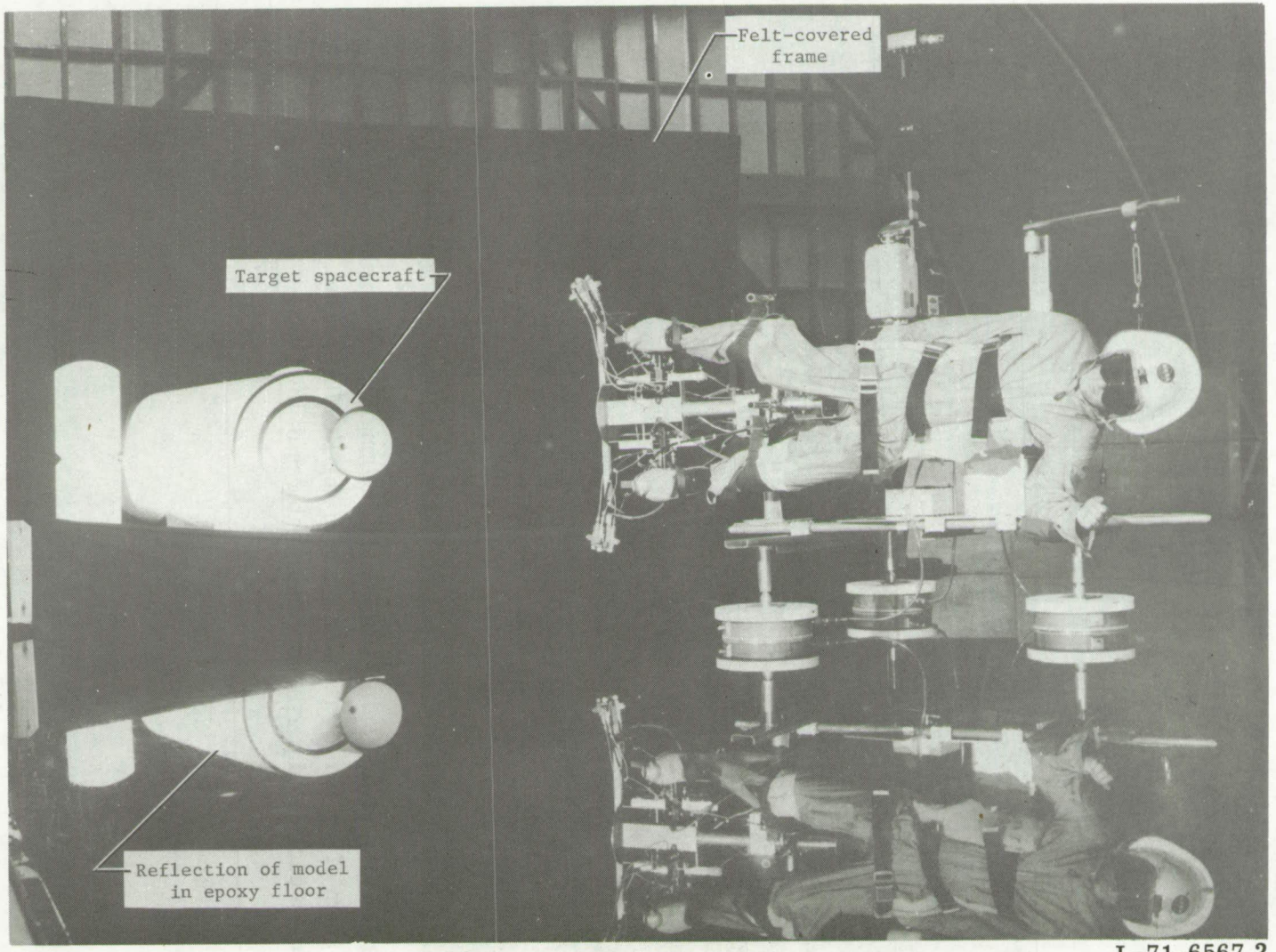


Figure 3.- Sketches of the original harness system used to attach the FCMU and the backpack to the test subject in order to retain a degree of waist mobility.



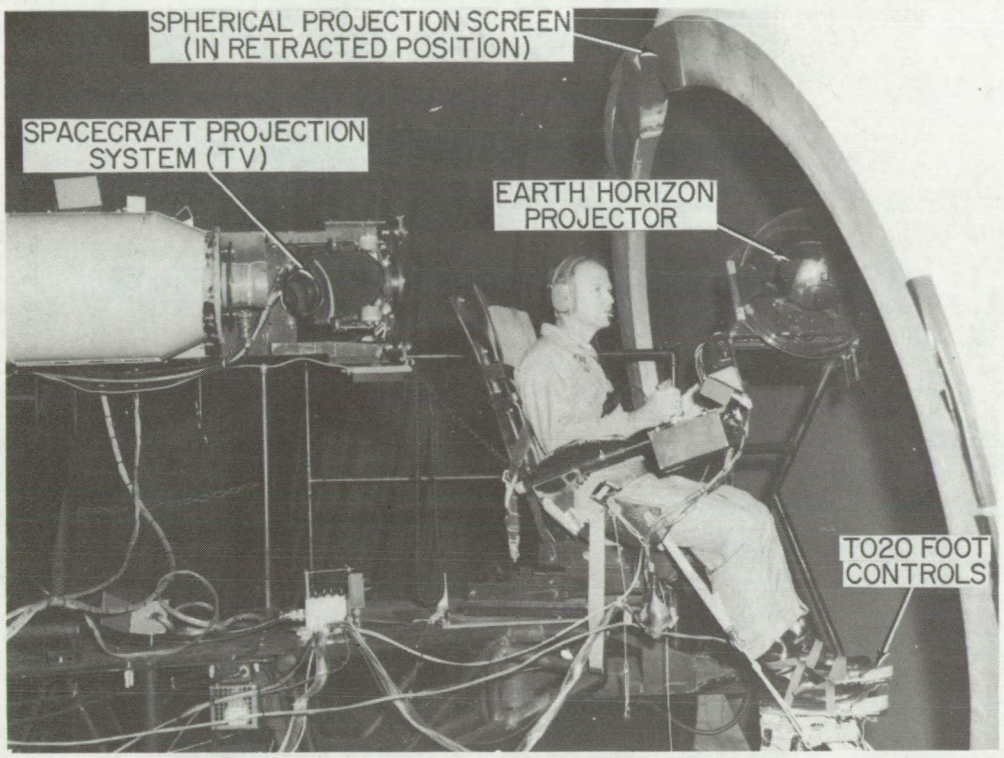
L-75-171

Figure 4.- View of test subject in the air-bearing simulator which provided freedom of motion in the pitch plane of the FCMU system. The partial mockup duplicated pertinent visual features of the OWS.



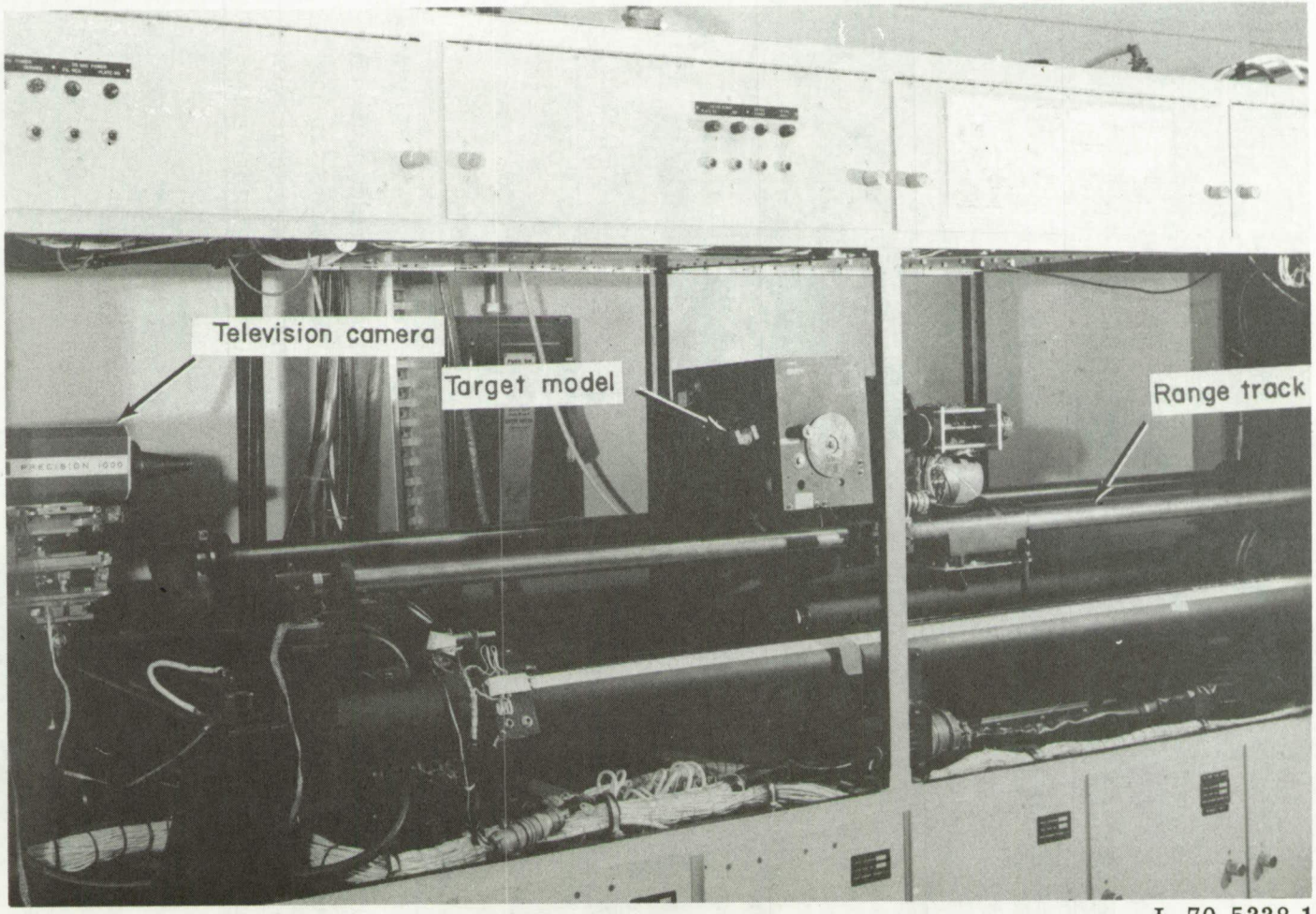
L-71-6567.2

Figure 5.- View illustrating the simulated extravehicular test conditions for the air-bearing simulator. The subject is shown in the research version of the FCMU mockup as used in earlier studies. The goggles used in those studies to suppress the ambient light were not employed for the current studies.



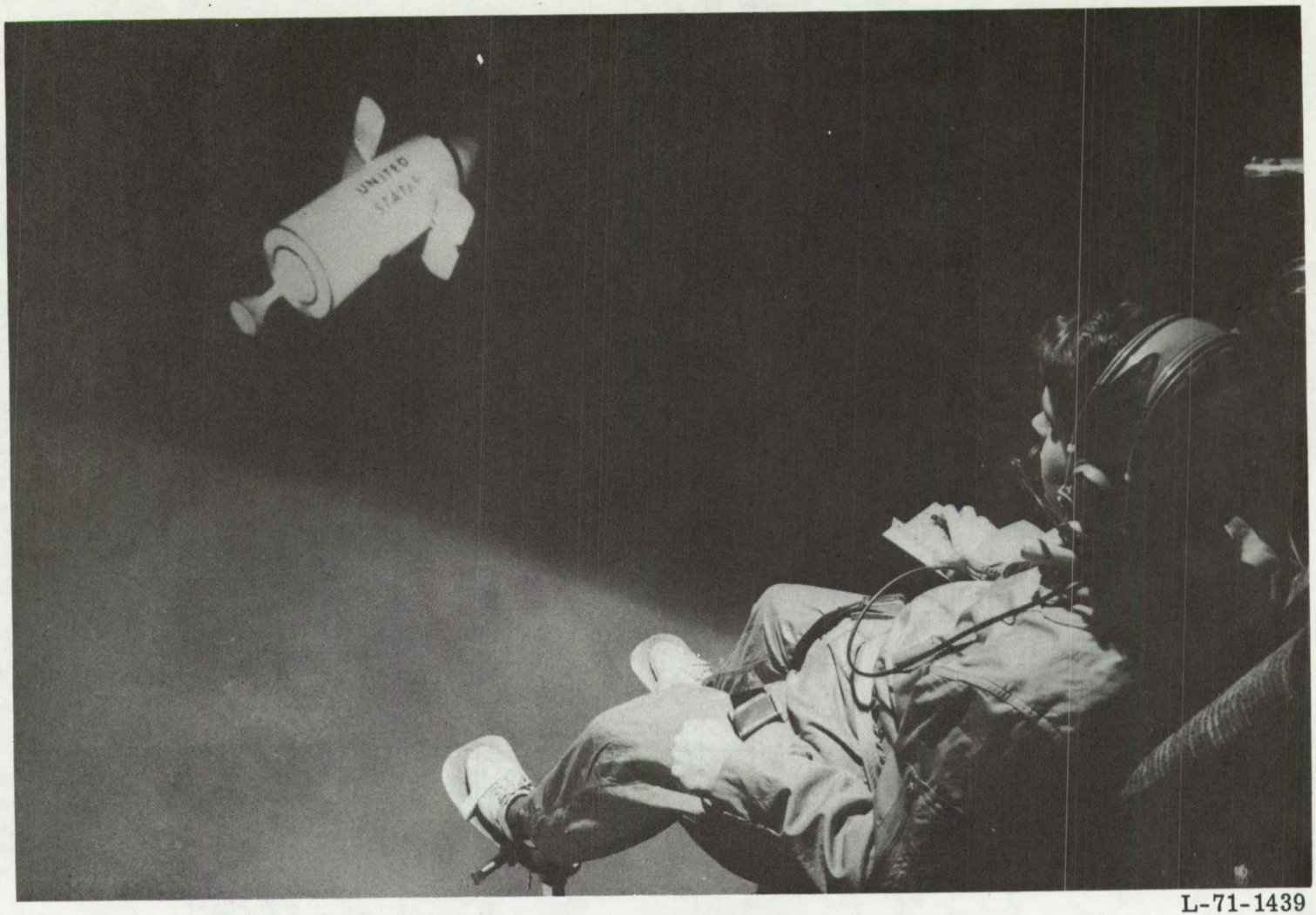
L-75-172

Figure 6.- View of test subject seated in the visual-task simulator used for training and baseline data measurements. The projection screen has been moved in order to show the equipment. The 6.1-meter-diameter spherical screen is normally positioned with the subject at the center.



L-70-5338.1

Figure 7.- View of television camera and model drive system used to generate the visual image of the target spacecraft for the visual-task simulator.



L-71-1439

Figure 8.- View of subject seated on the FCMU in the visual-task simulator and observing the image of the target spacecraft as projected on the spherical screen.

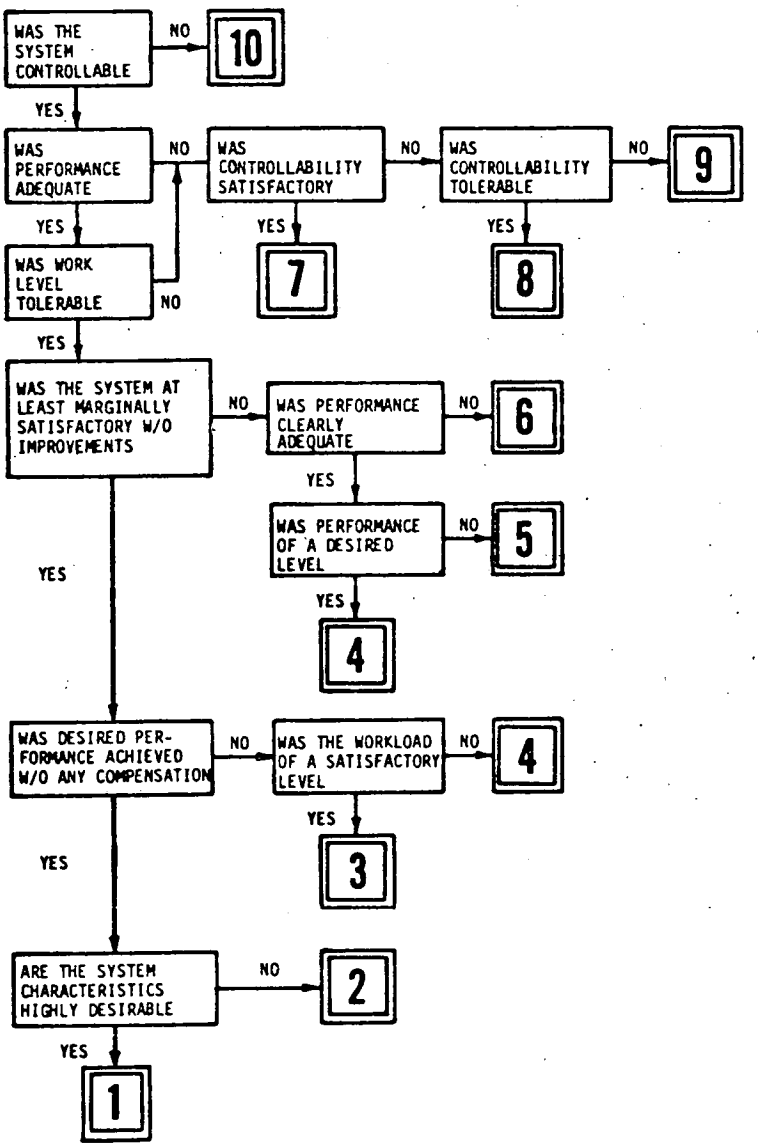
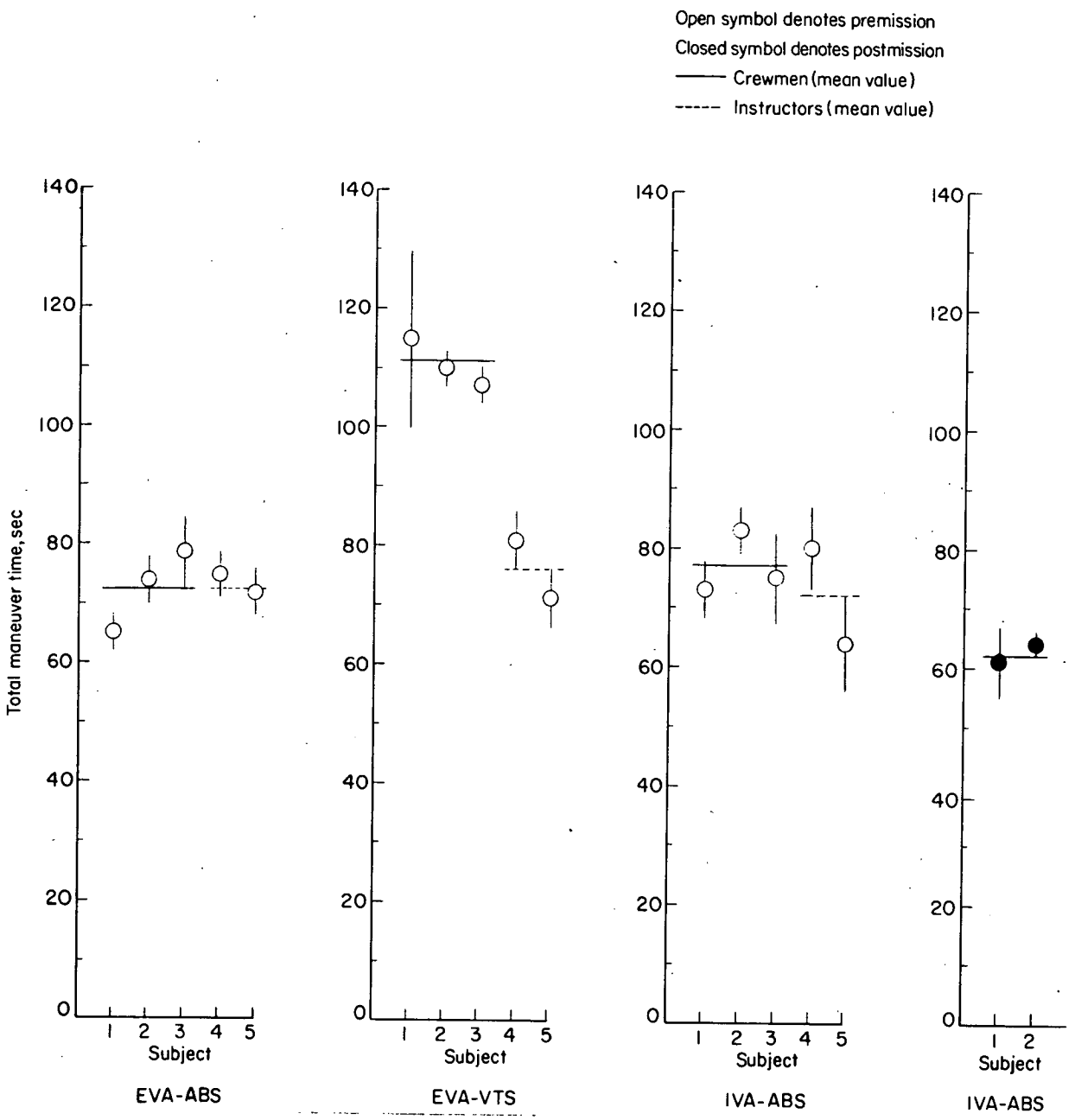
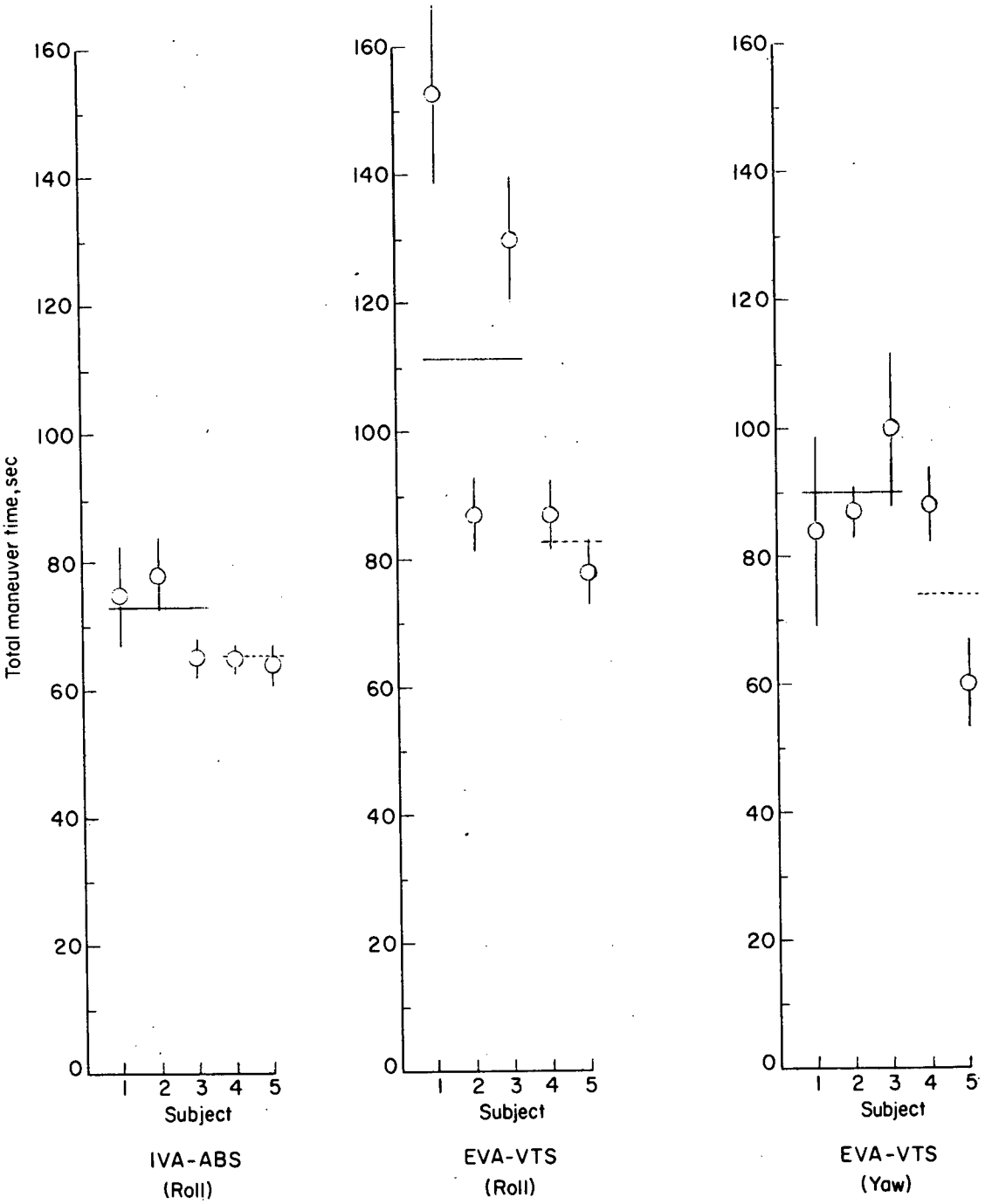


Figure 9.- Chart used as an aid in assigning pilot ratings for various test maneuvers performed with the FCMU.



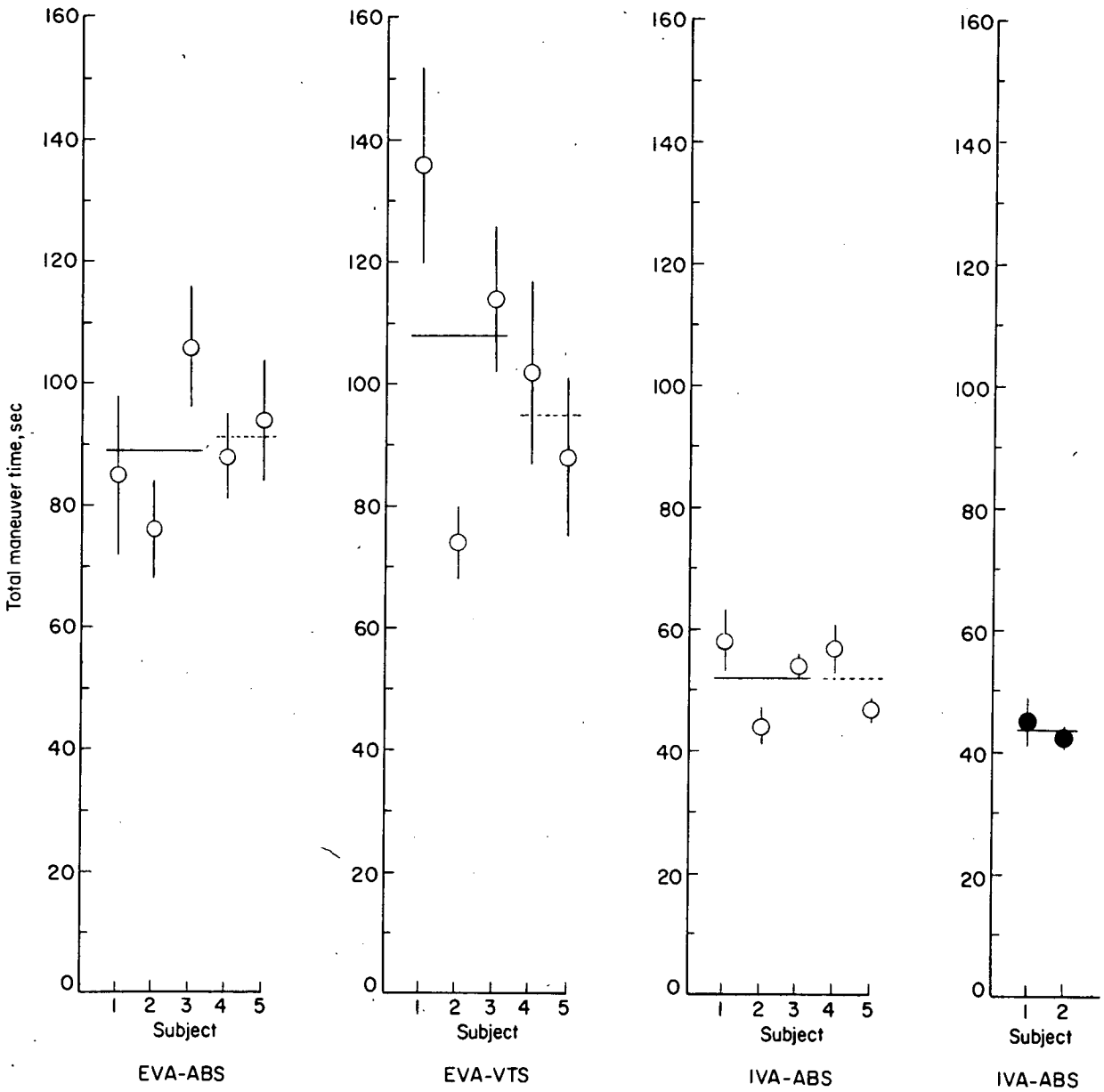
(a) Pitch-attitude change and hold maneuver.

Figure 10.- Plots of mean and standard deviation values for the total maneuvering times of each test maneuver performed by each test subject under each of the simulated test conditions.



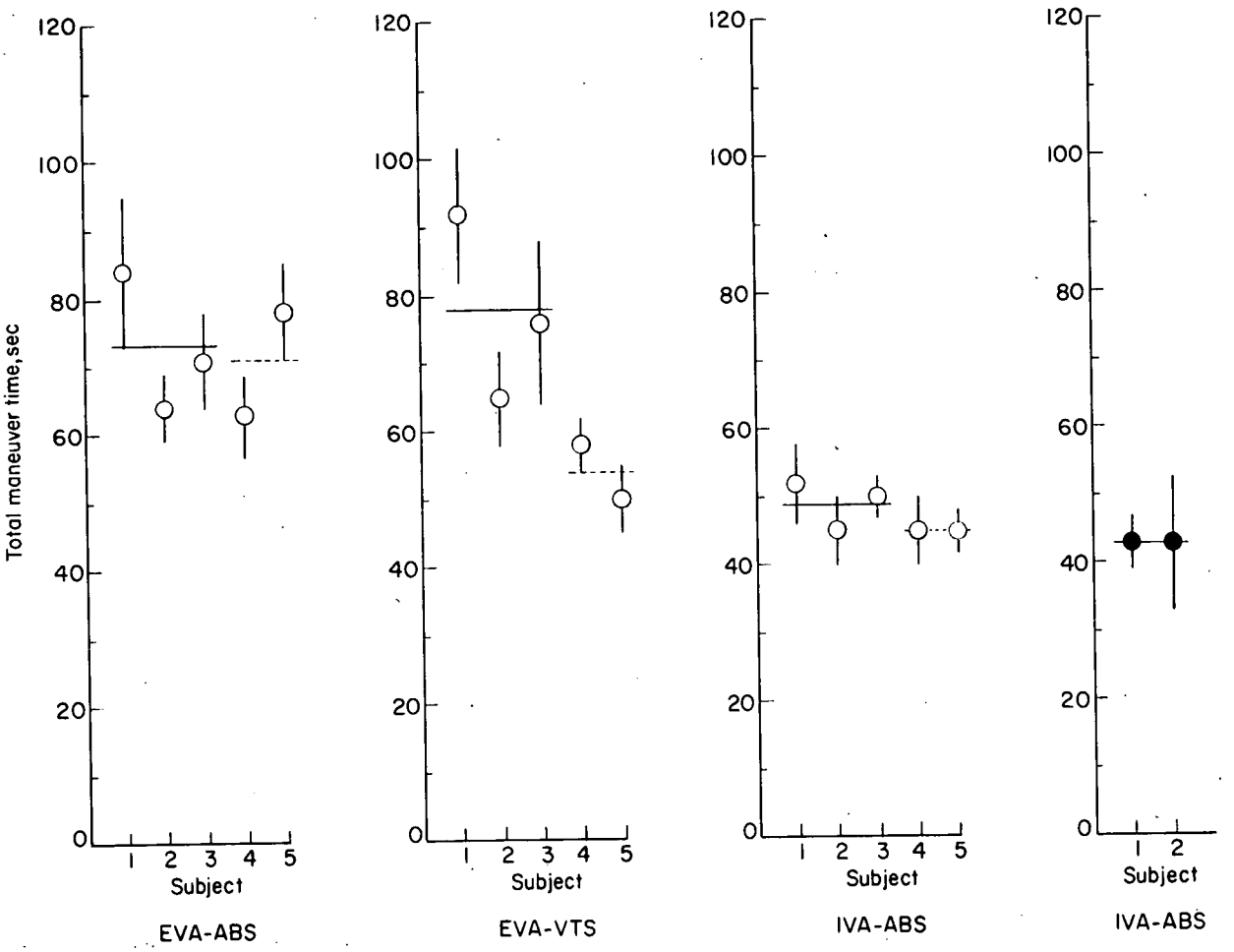
(b) Roll- and yaw-attitude change and hold maneuvers.

Figure 10.- Continued.



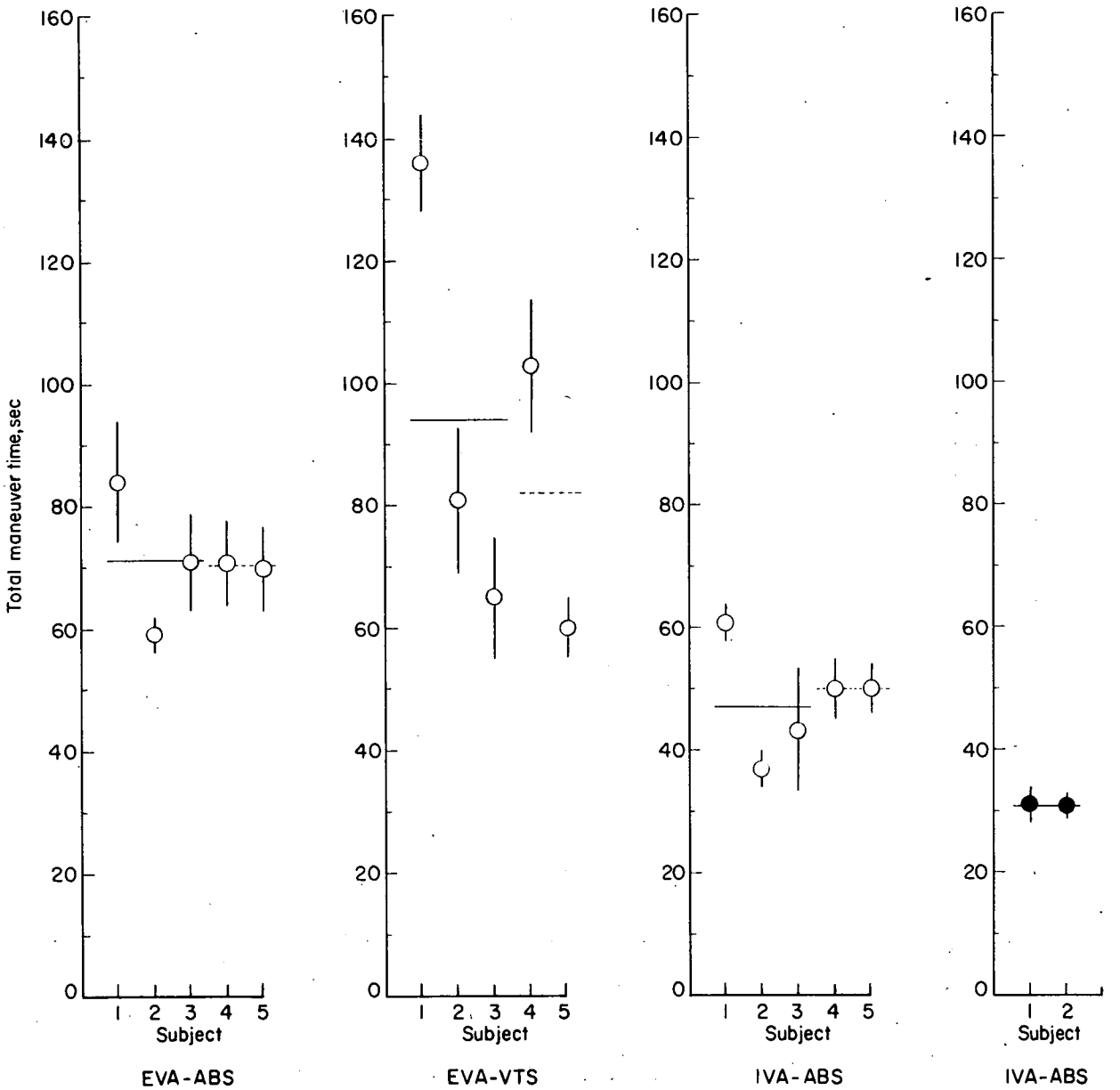
(c) Single axis.

Figure 10.- Continued.



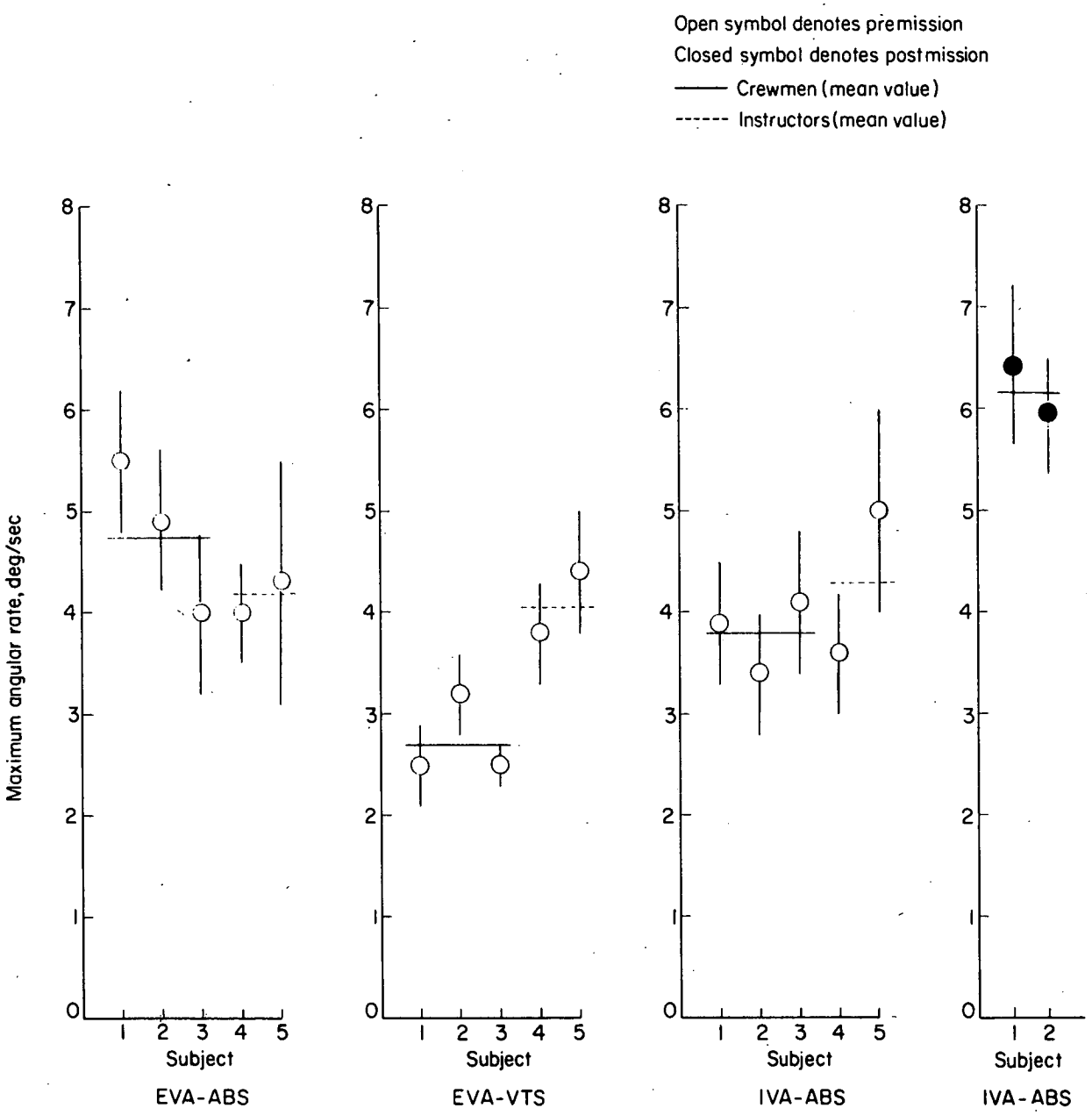
(d) Double axis.

Figure 10.- Continued.



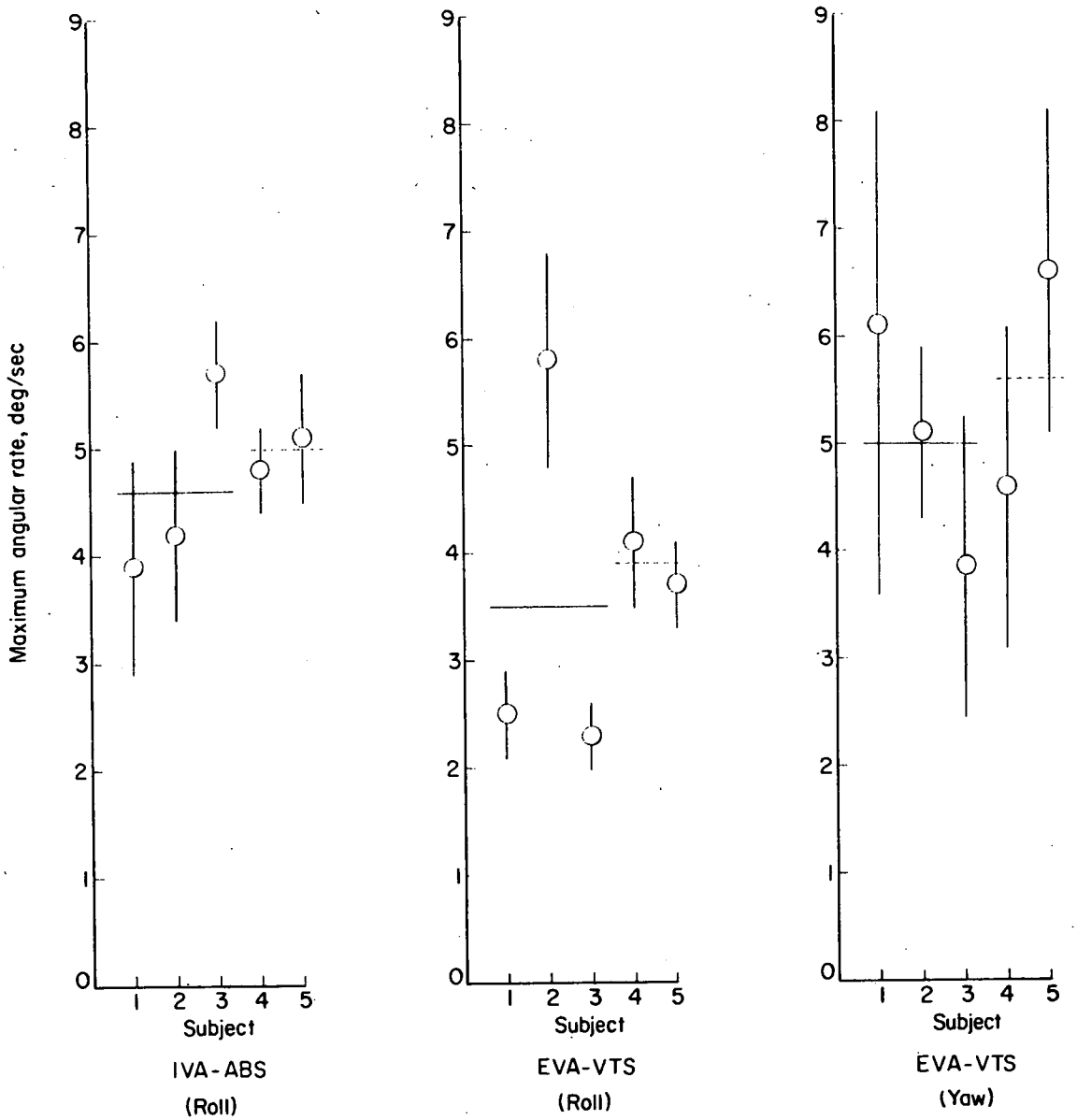
(e) Dogleg.

Figure 10.- Concluded



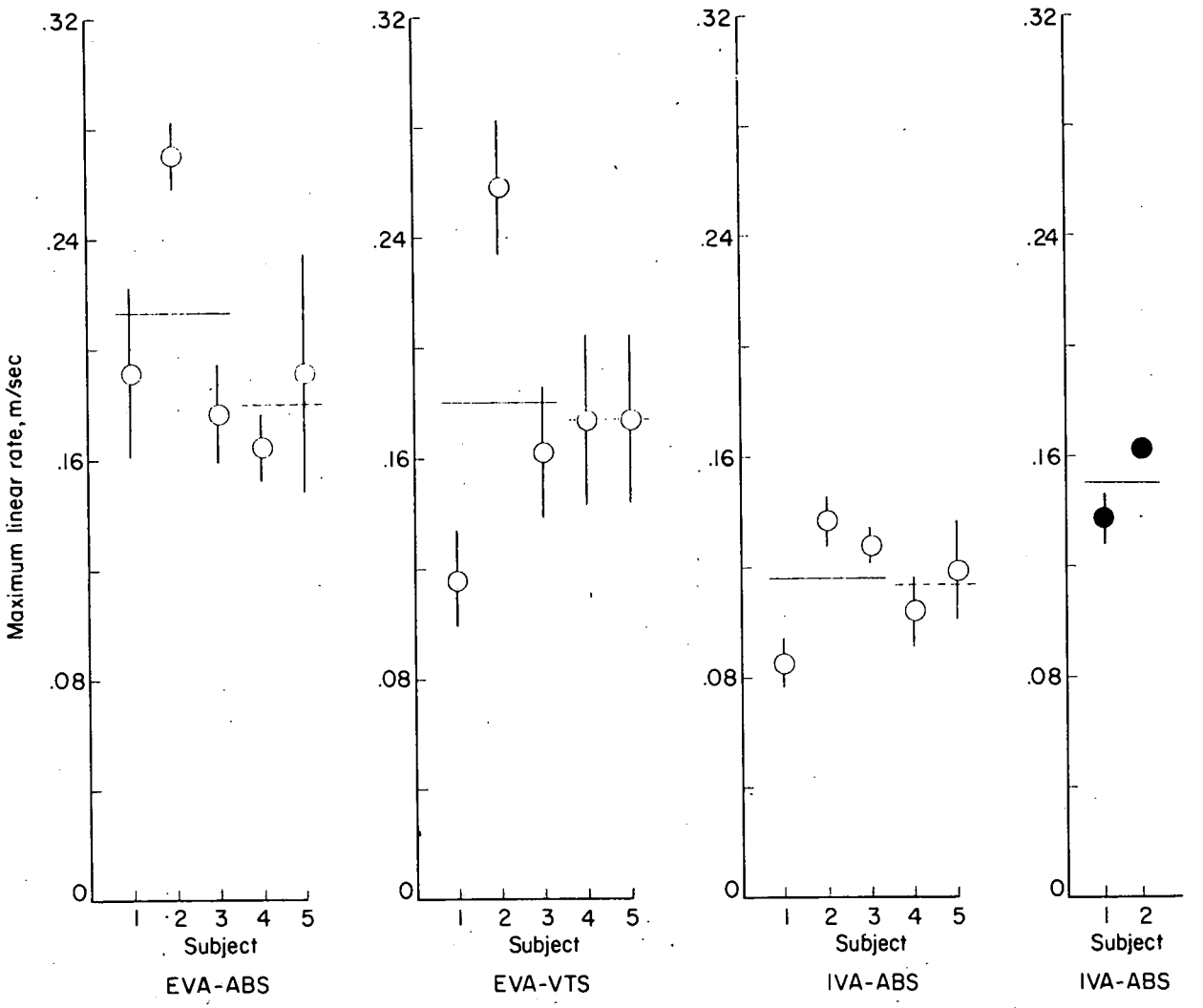
(a) Pitch-attitude change and hold maneuver.

Figure 11.- Plots of mean and standard deviation values for the maximum angular rates for the attitude maneuvers and the maximum linear rates for the translation maneuvers performed by each of the test subjects under each of the test conditions.



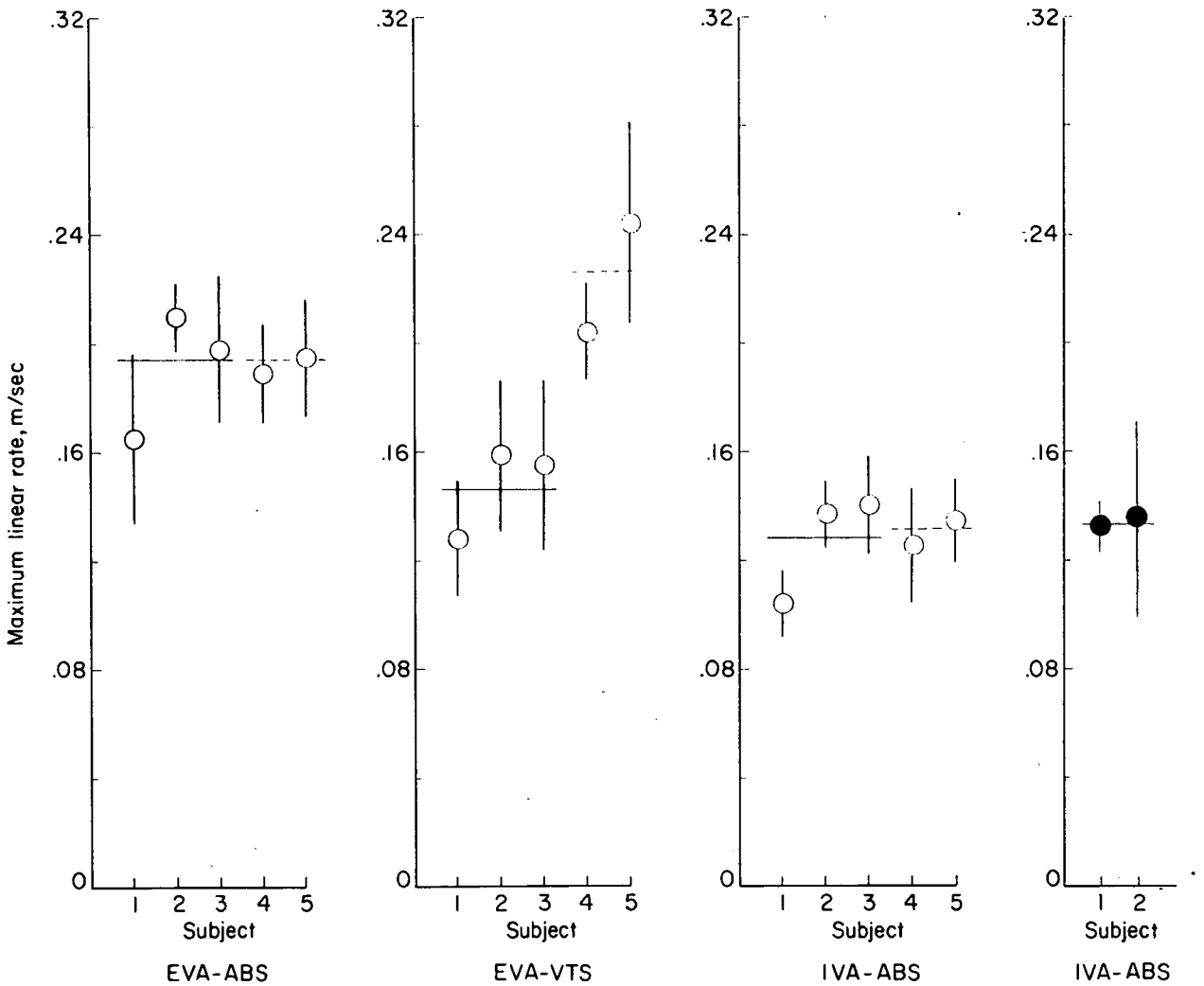
(b) Roll- and yaw-attitude change and hold maneuvers.

Figure 11.- Continued.



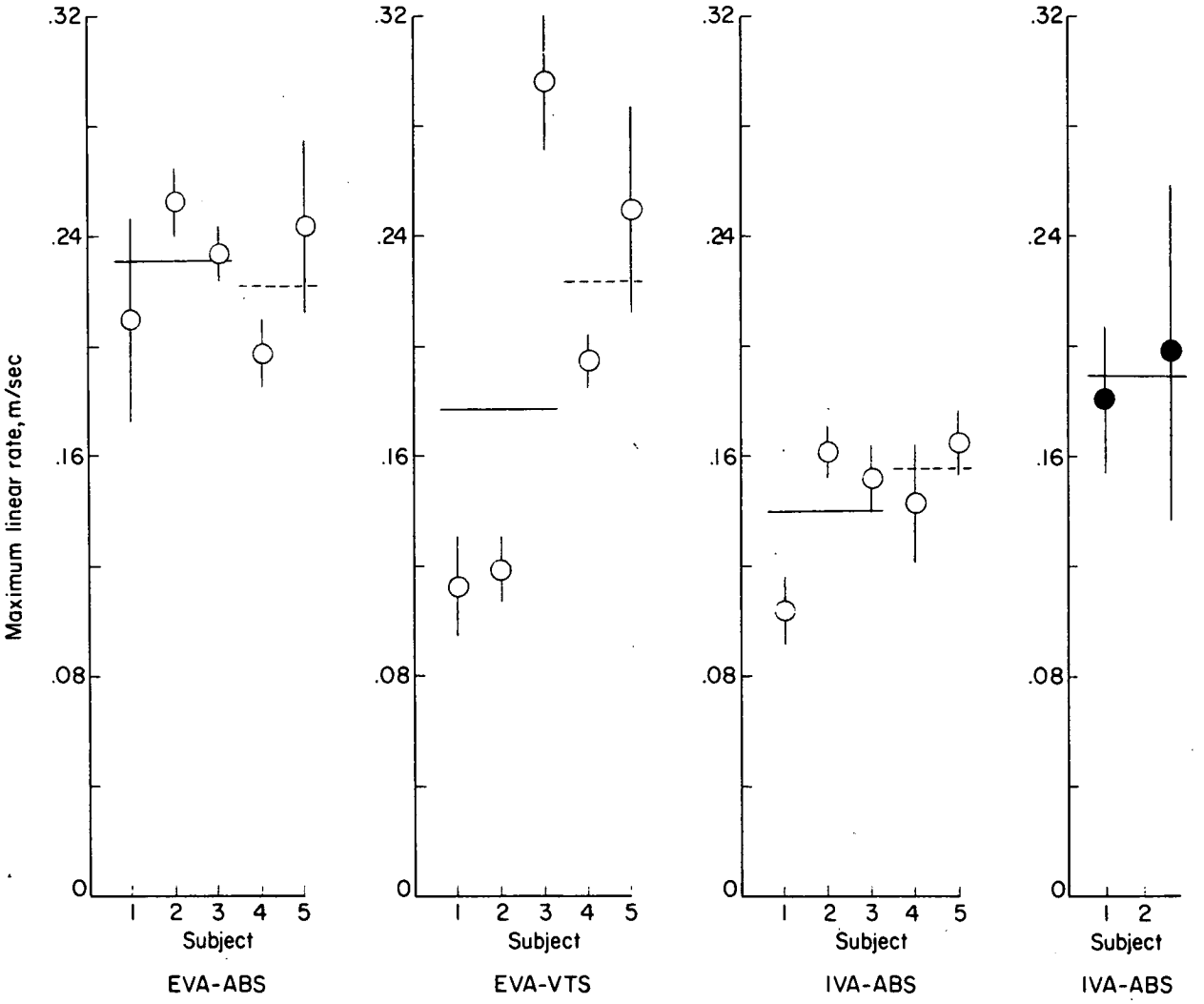
(c) Single axis.

Figure 11.- Continued.



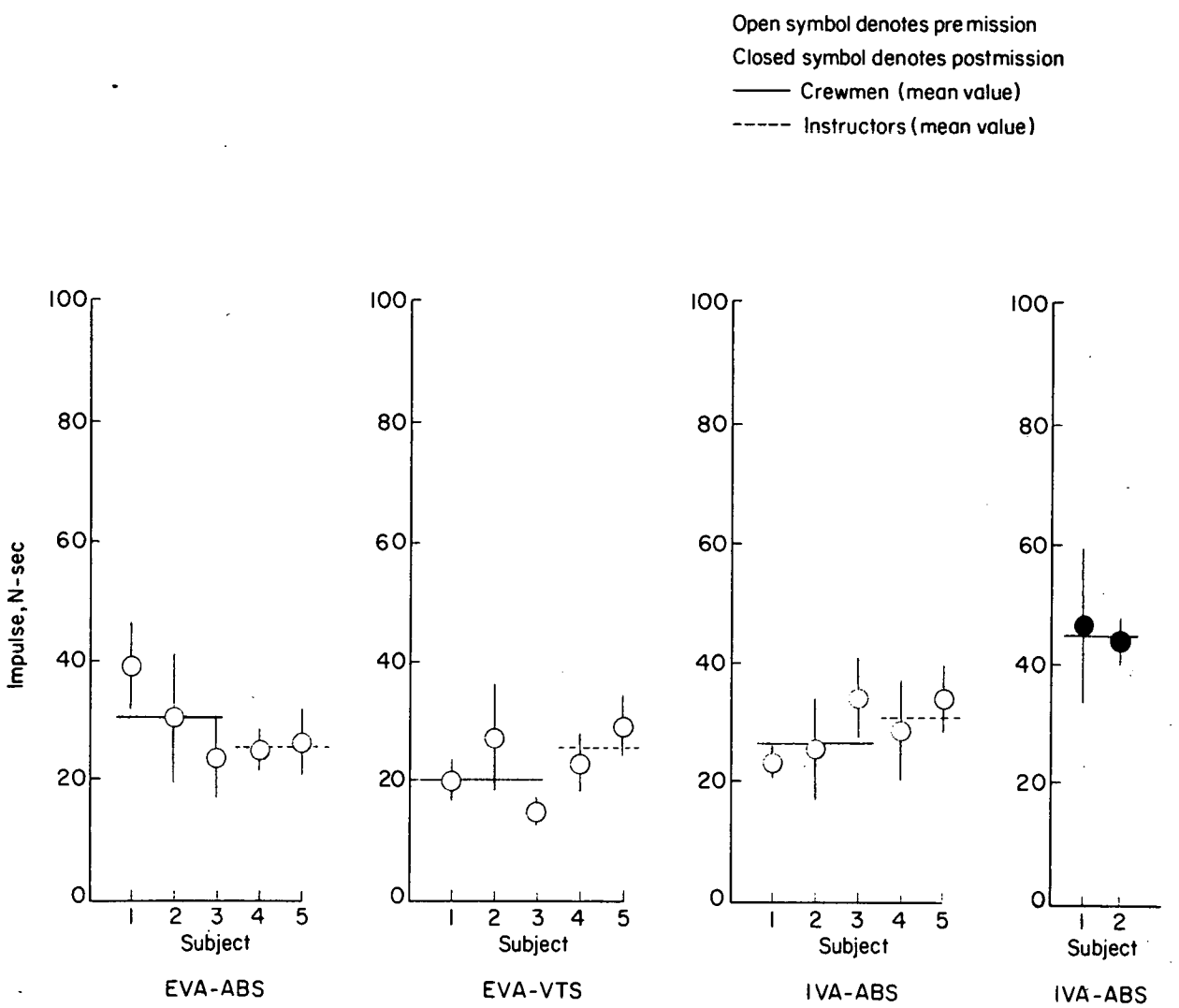
(d) Double axis.

Figure 11.- Continued.



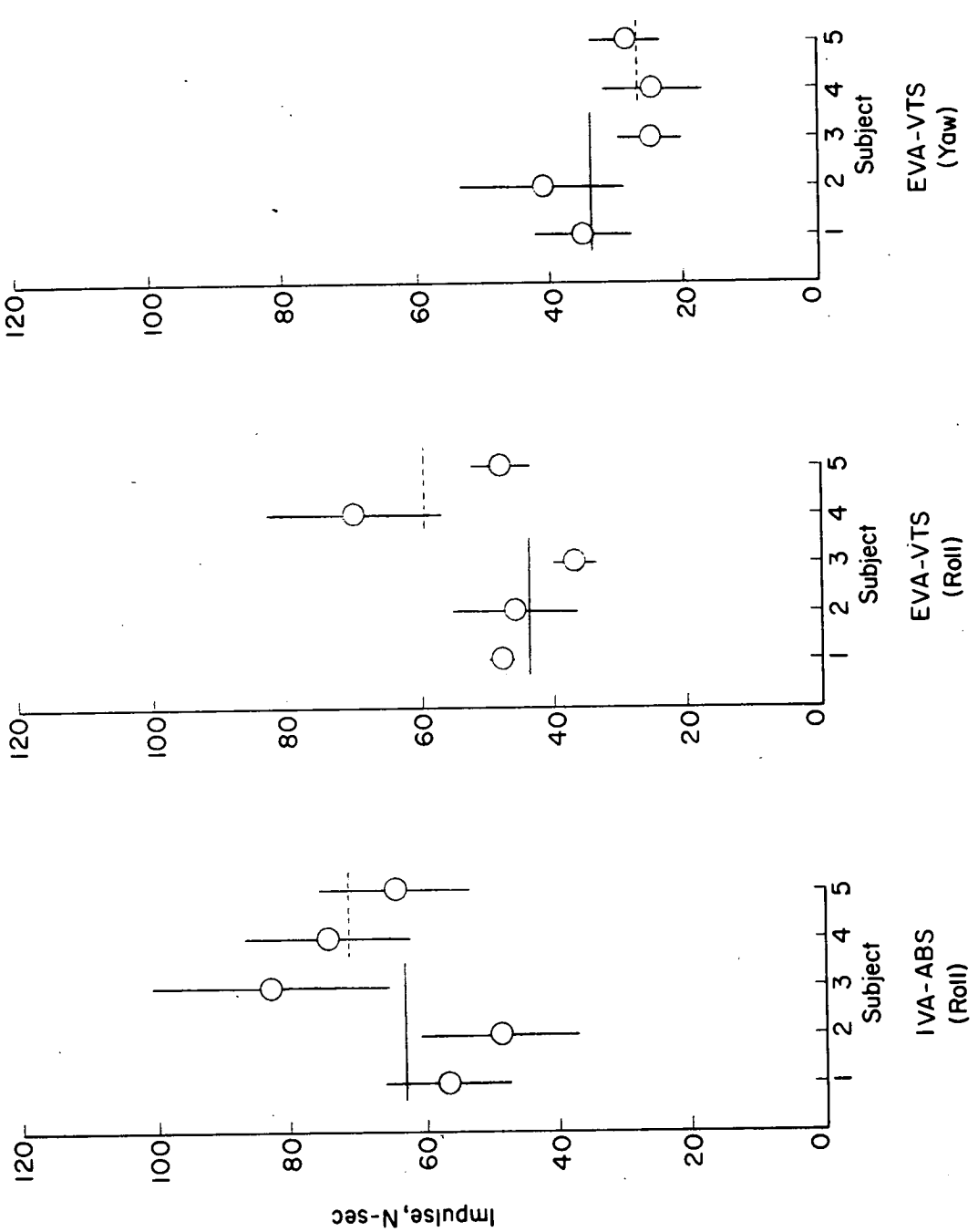
(e) Dogleg.

Figure 11.- Concluded.



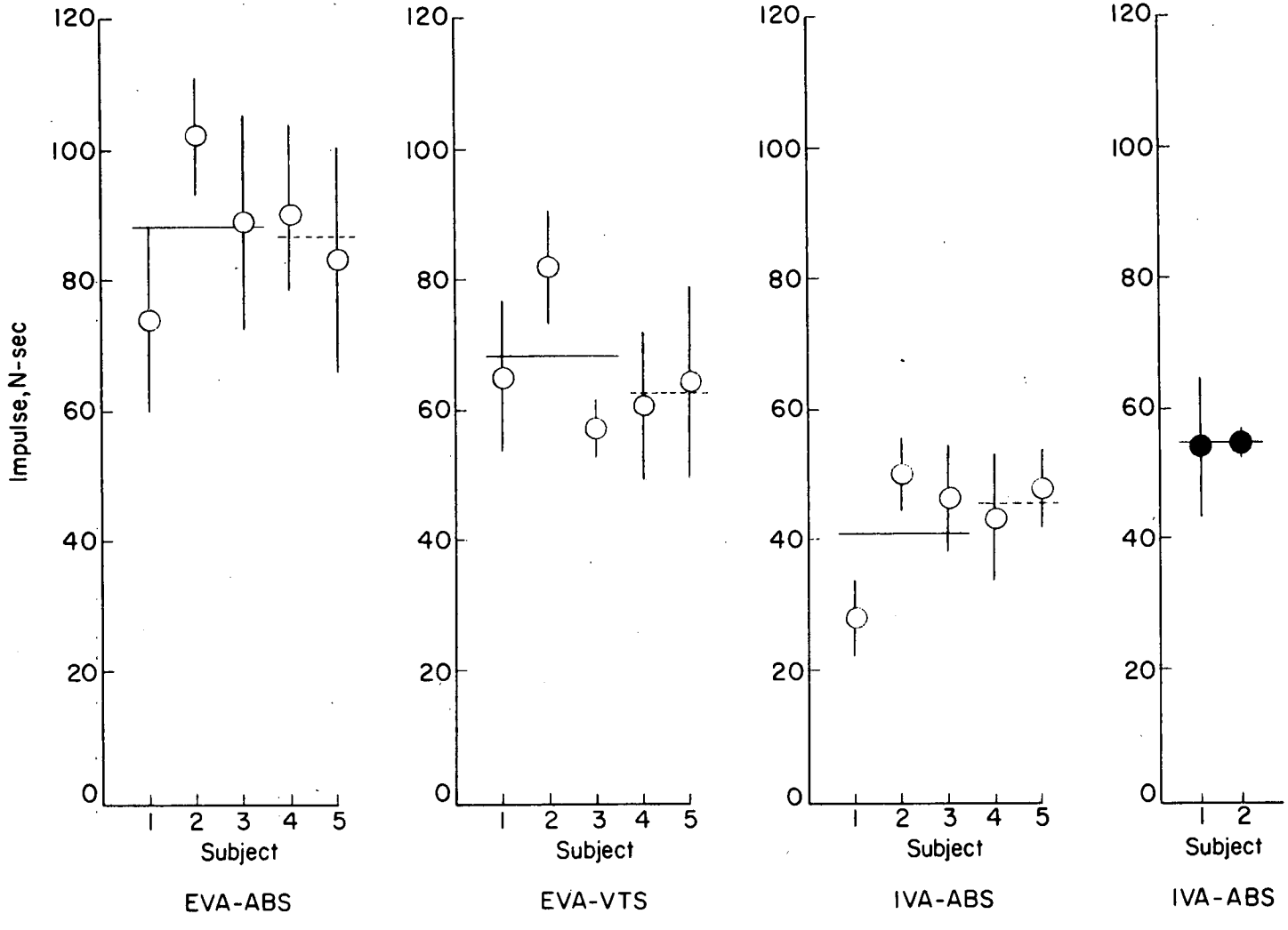
(a) Pitch-attitude change and hold maneuver.

Figure 12.- Plots of mean and standard deviation values for the total impulse of each test maneuver performed by each test subject under each of the test conditions.



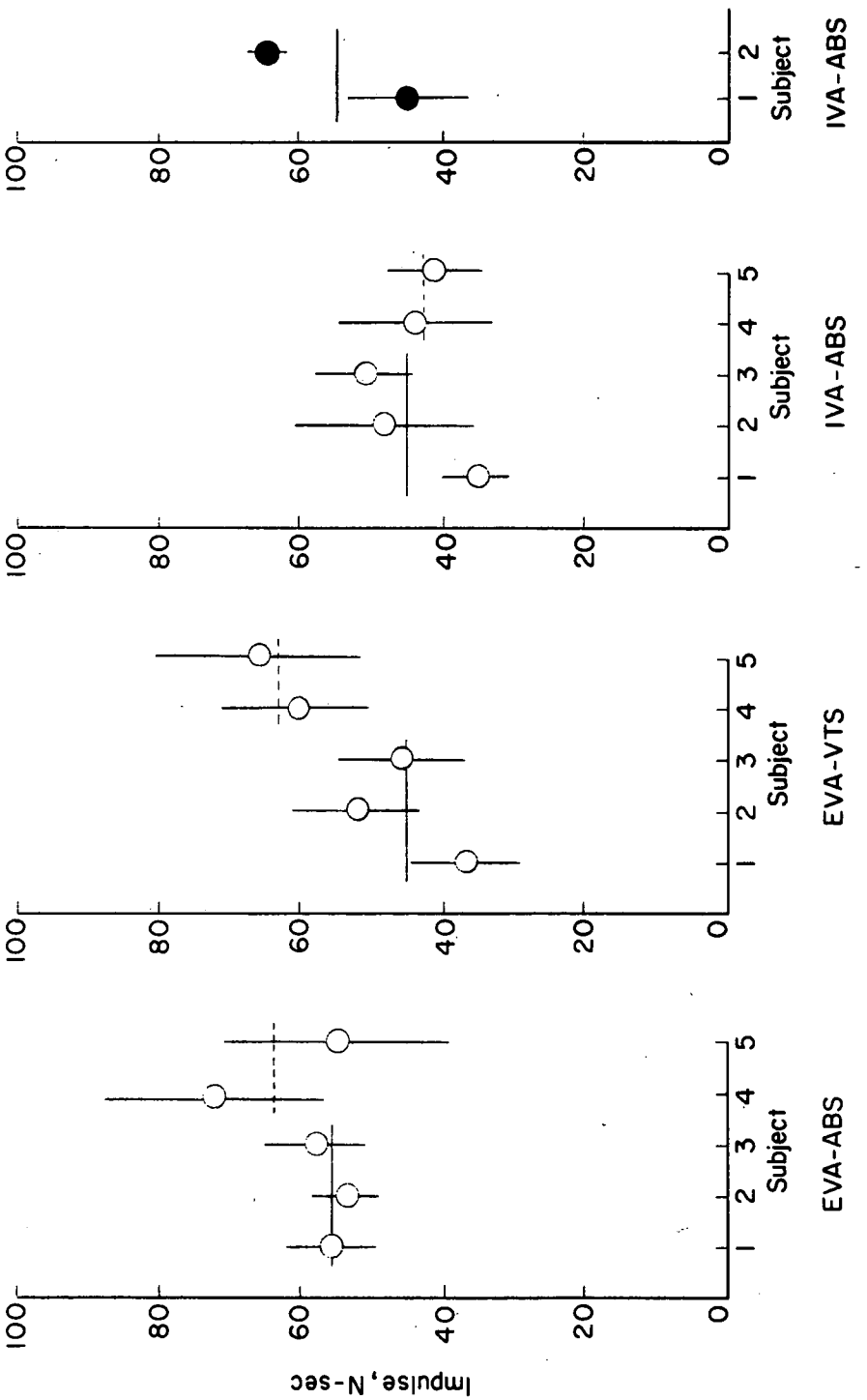
(b) Roll- and yaw-attitude change and hold maneuvers.

Figure 12.- Continued.



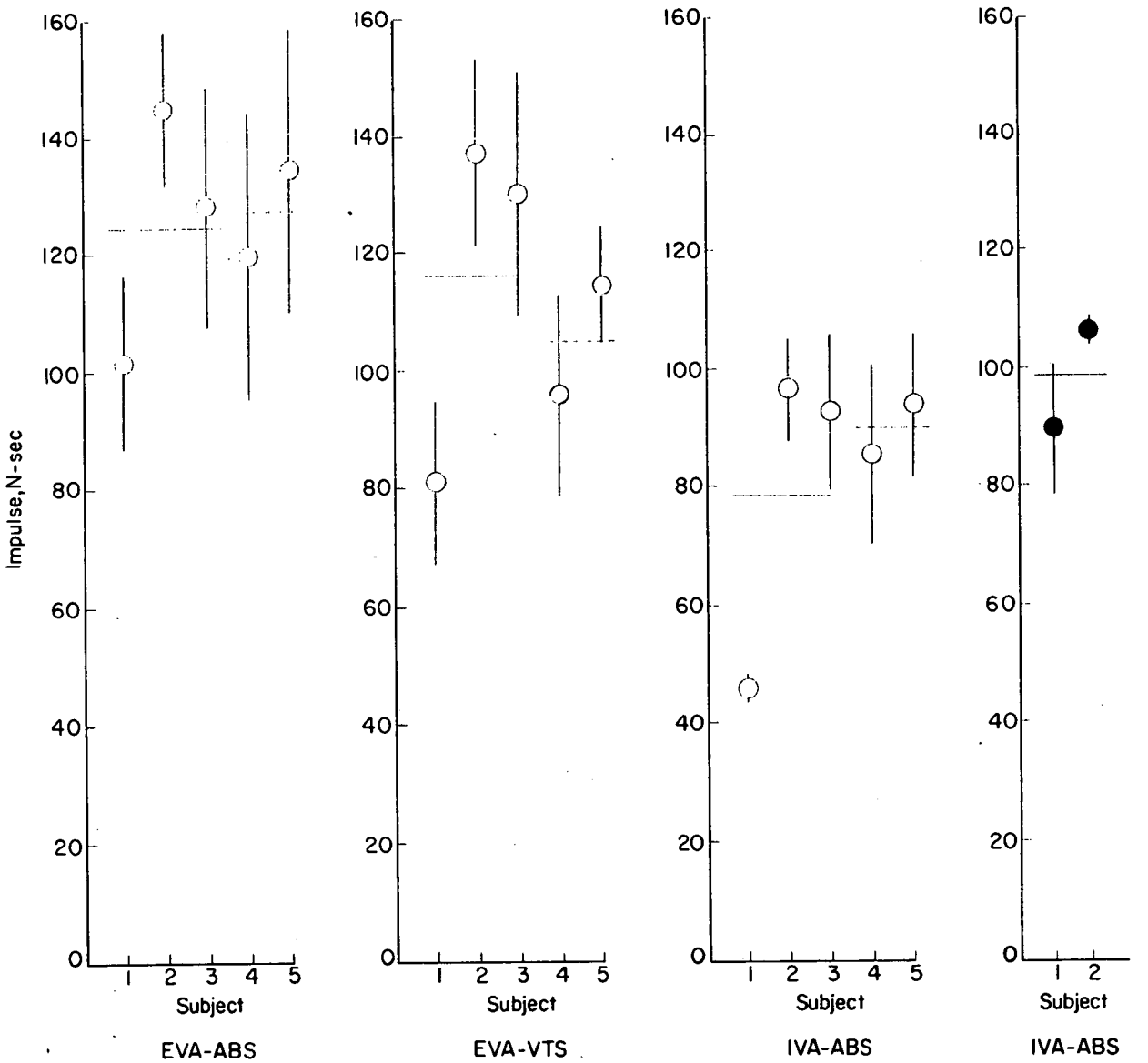
(c) Single axis.

Figure 12.- Continued.



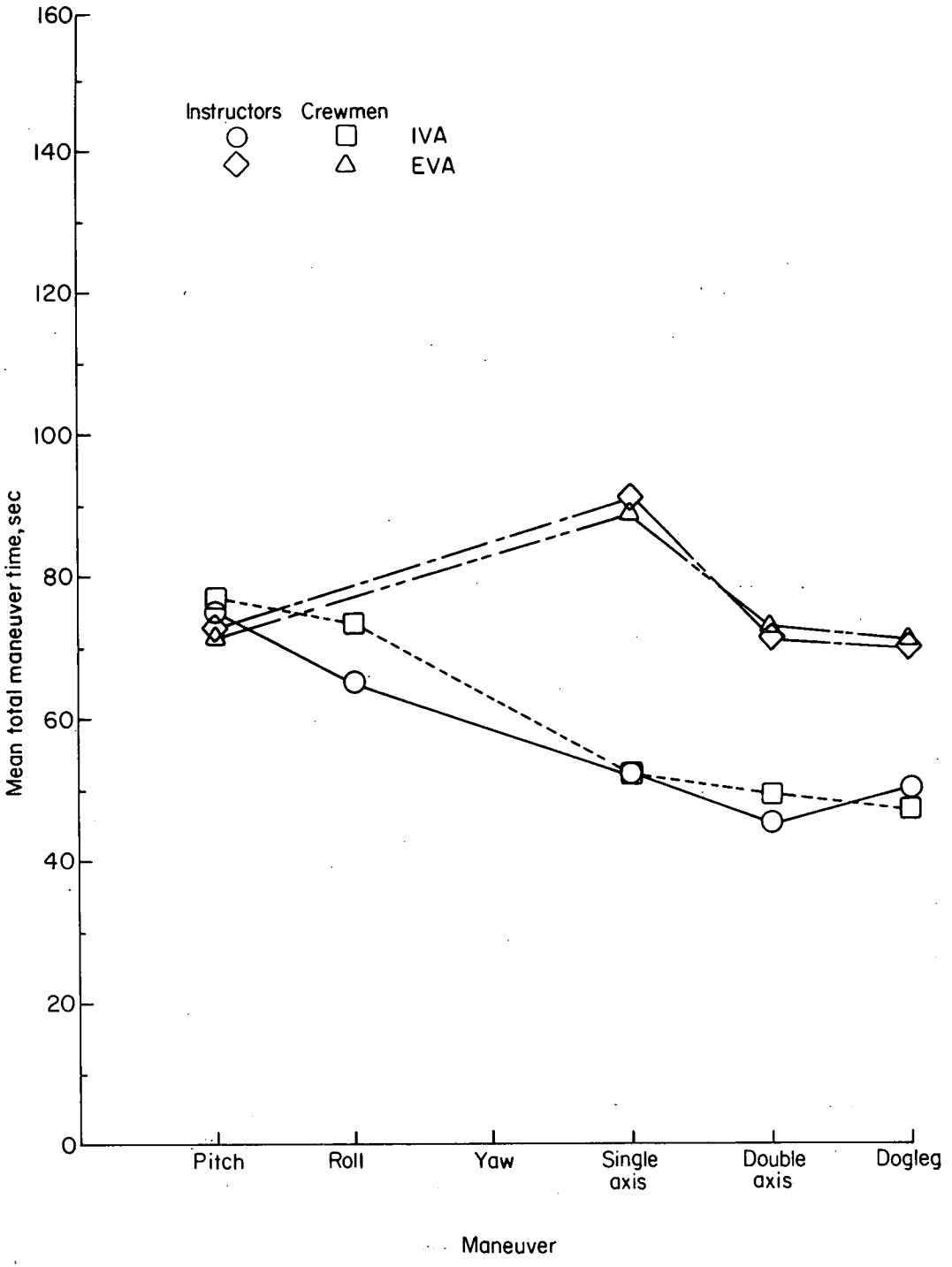
(d) Double axis.

Figure 12.- Continued.



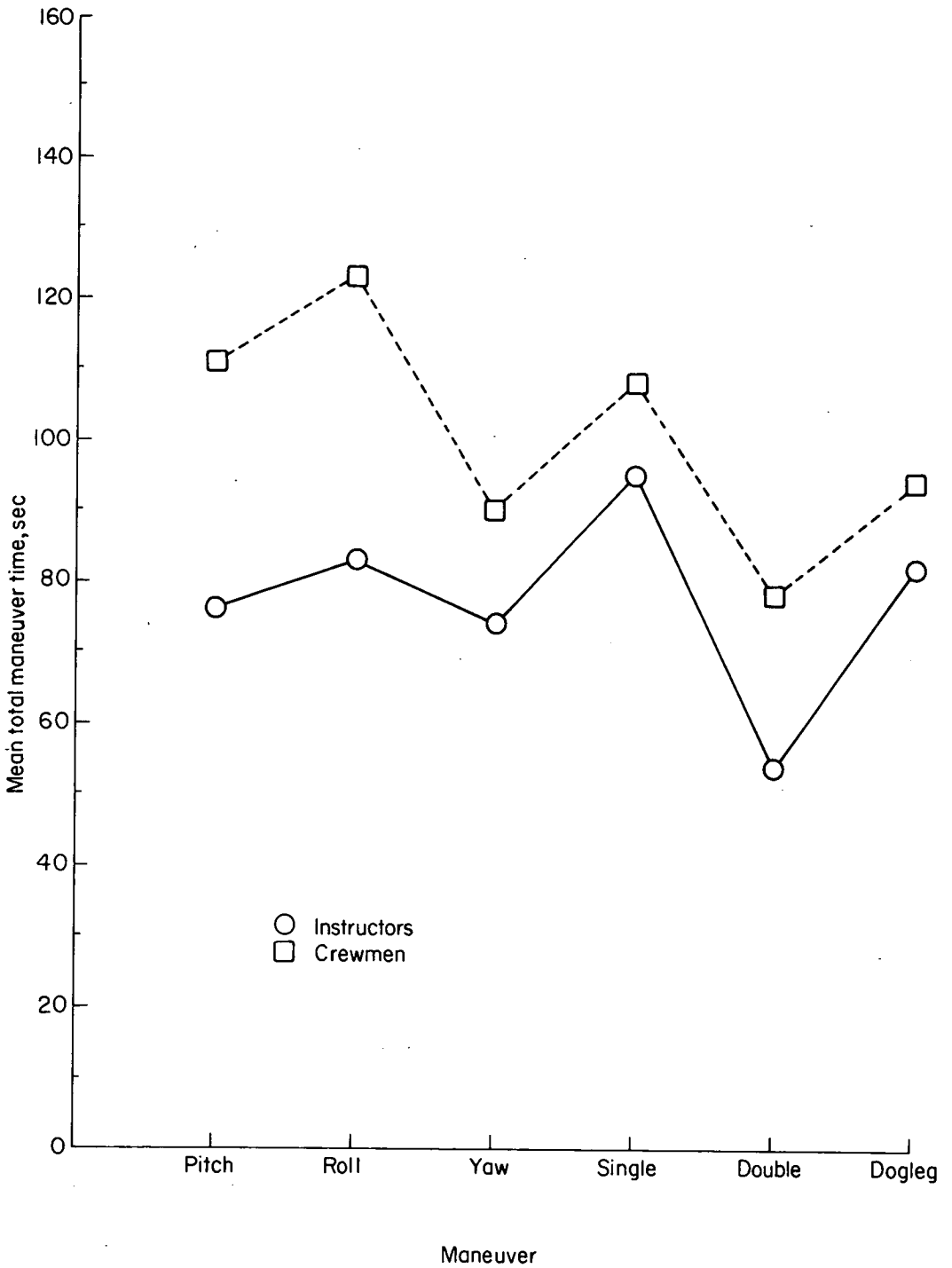
(e) Dogleg.

Figure 12.- Concluded.



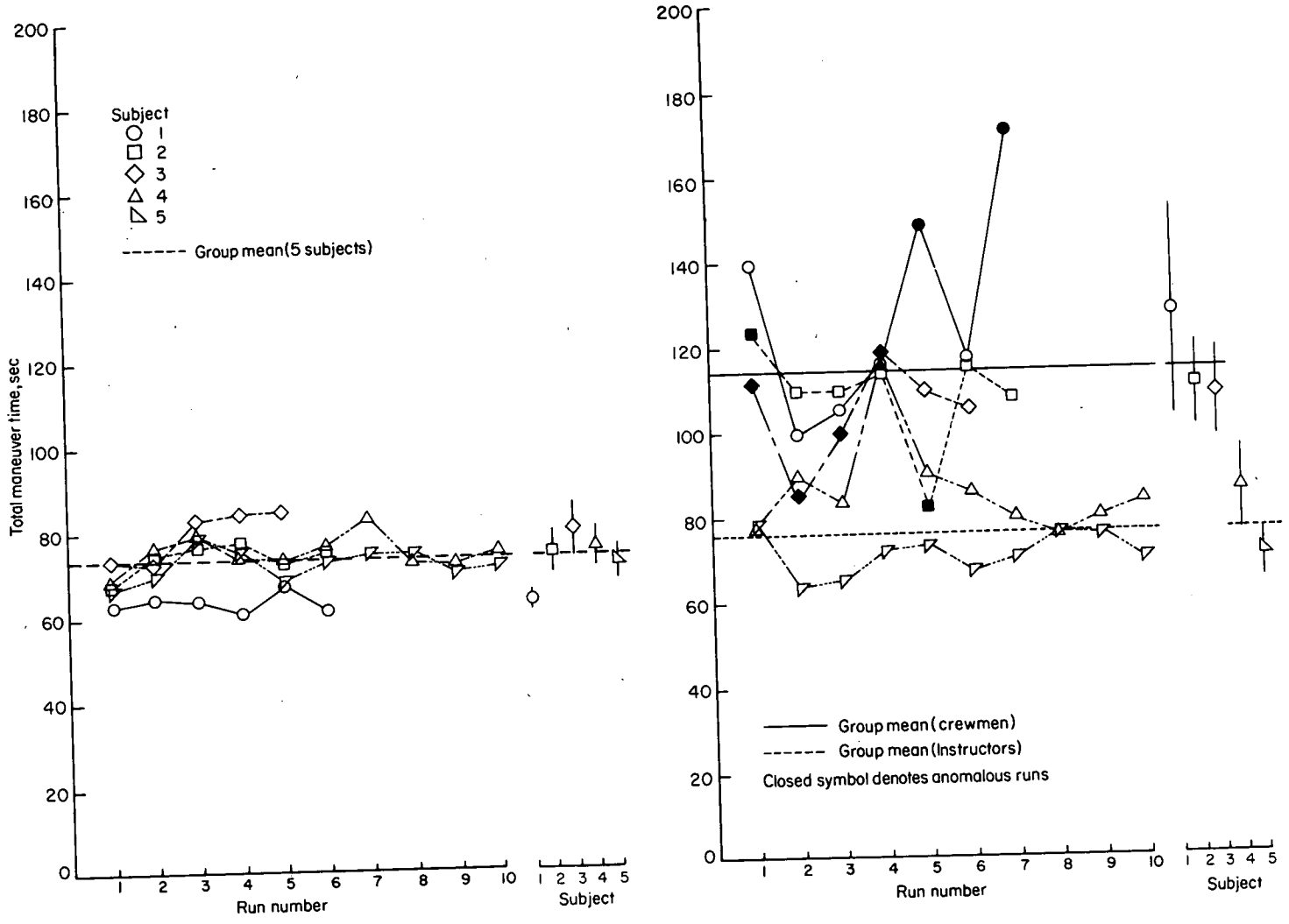
(a) ABS for the IVA and EVA conditions.

Figure 13.- Comparisons of group mean values for the total maneuver times for the various maneuvers performed in the air-bearing simulator (ABS) and the visual-task simulator (VTS) for the intravehicular (IVA) and extravehicular (EVA) conditions.



(b) ABS and VTS for the IVA condition.

Figure 13.- Concluded.



(a) ABS runs.

(b) VTS runs.

Figure 14.- Total maneuver times for all runs of the pitch-attitude maneuvers presented in the sequence performed by each subject in the ABS and VTS for the EVA condition. Mean and standard deviation for each subject are shown at the right of each plot.

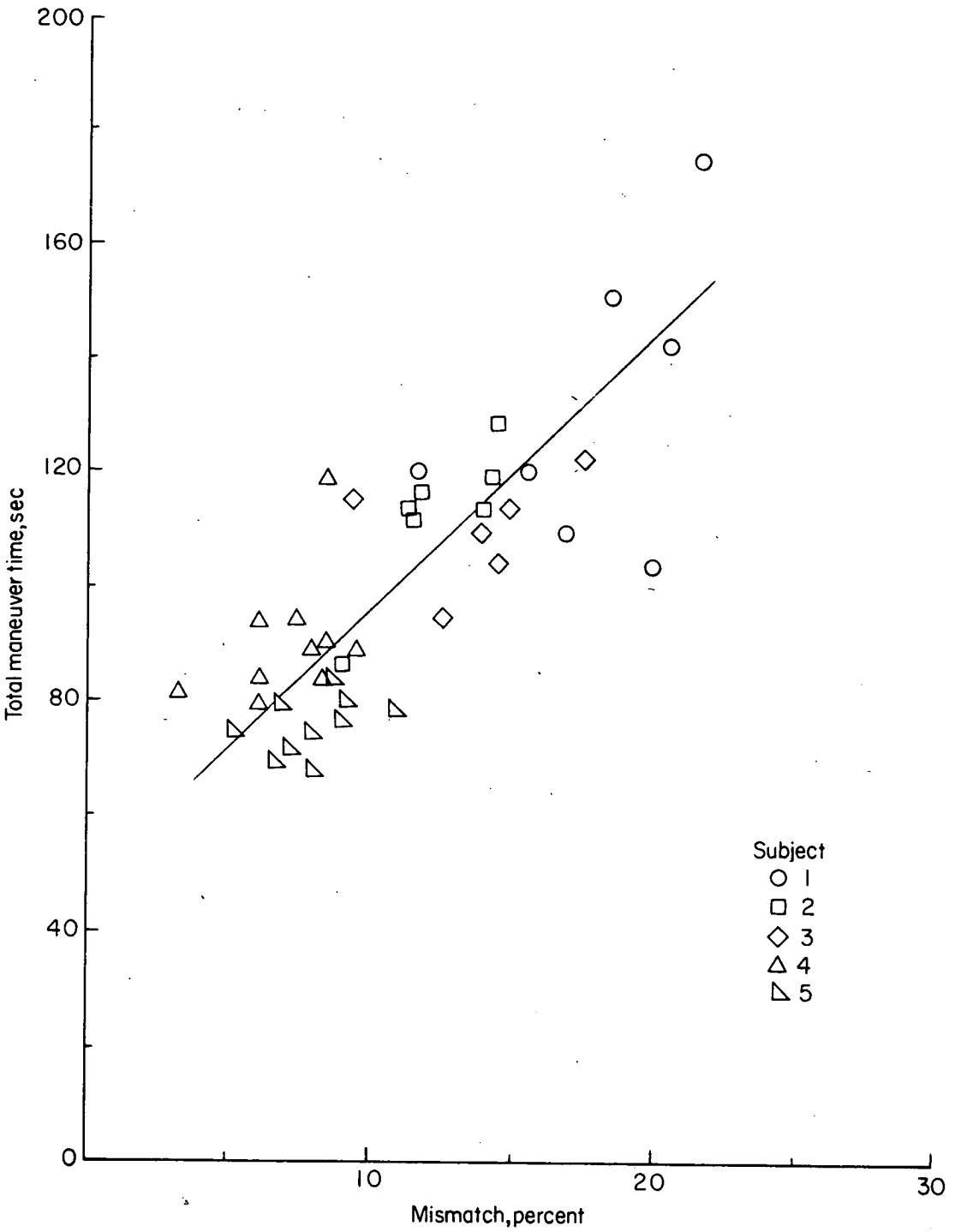
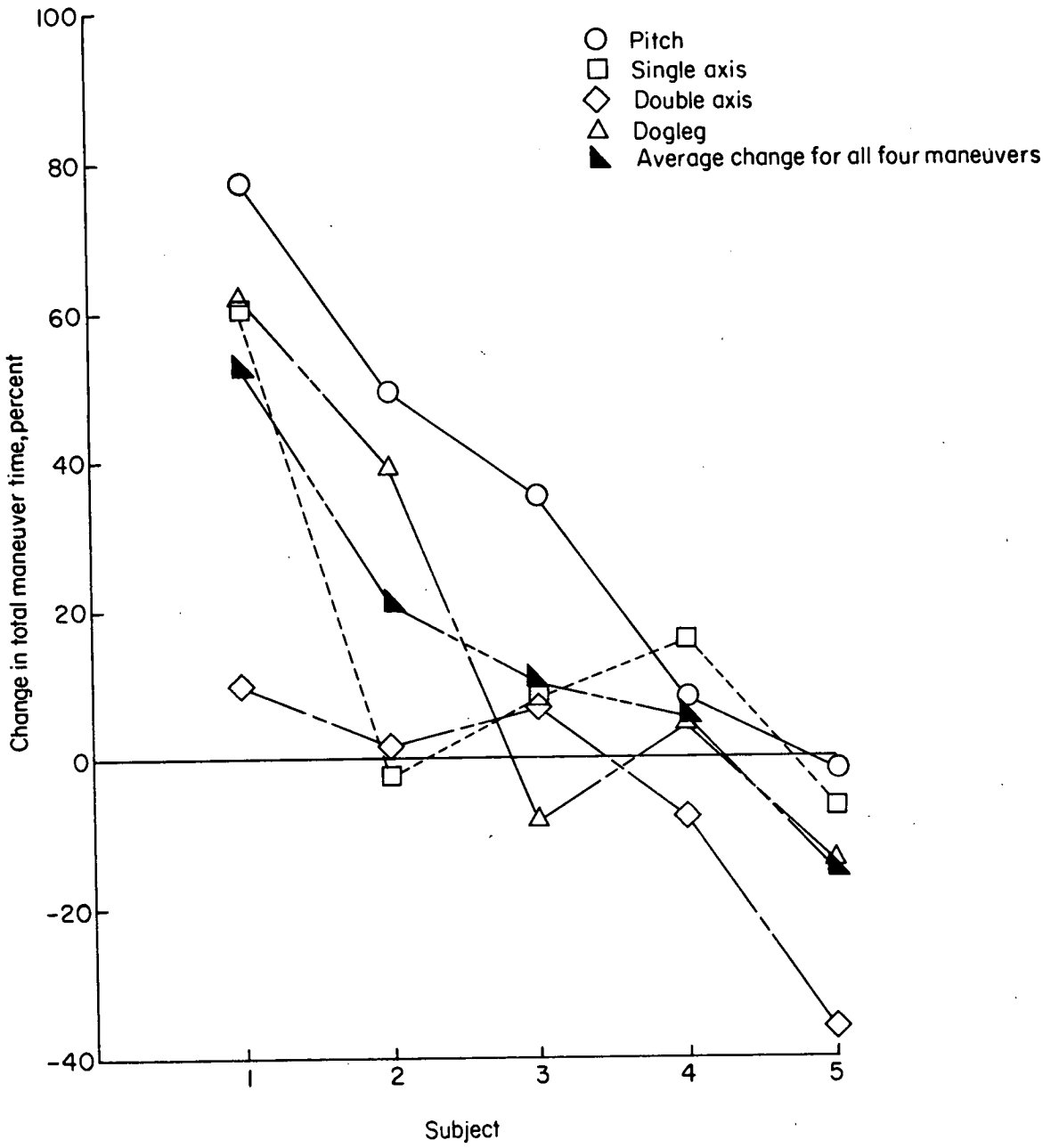
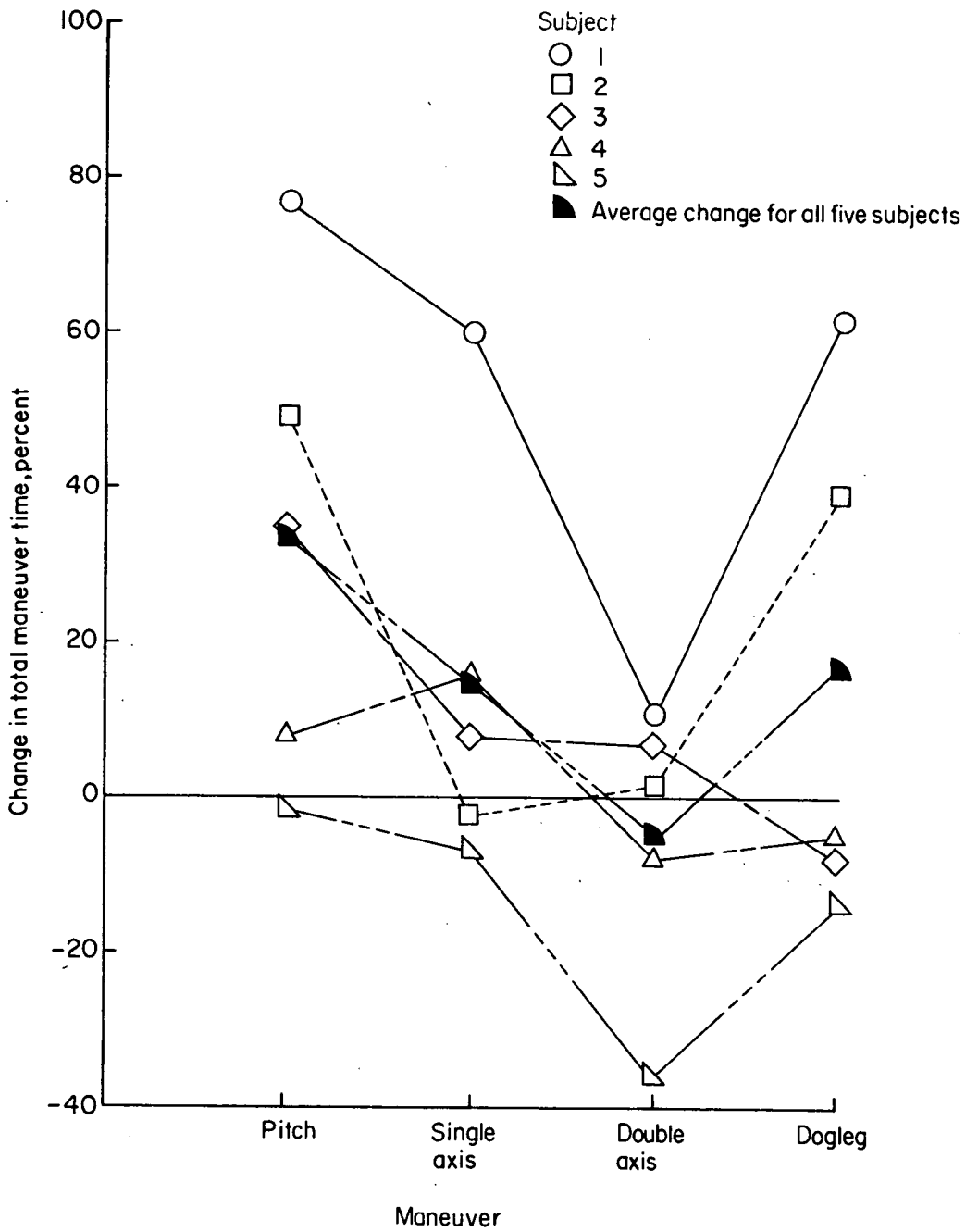


Figure 15.- Correlation of mismatch values and total maneuver times for the pitch-attitude maneuver as performed by each test subject in the VTS for the EVA condition.



(a) Comparison on the basis of subjects.

Figure 16.- Percent change in each subject's mean performance times of each maneuver for the VTS as compared with those for the ABS.



(b) Comparison on the basis of the maneuvers. (The sequence in which they were performed is shown from left to right.)

Figure 16.- Concluded.

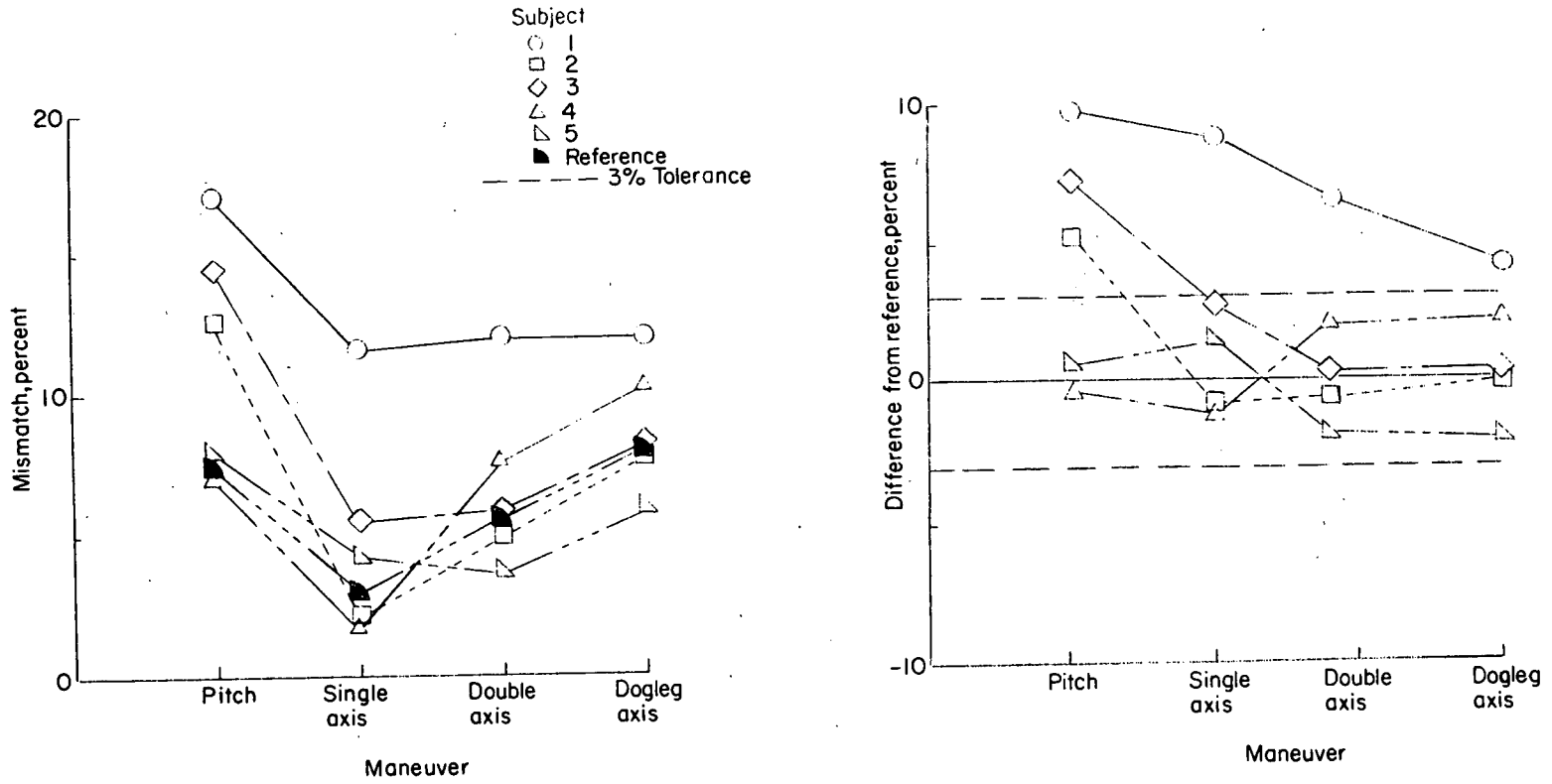


Figure 17.- Plots of the mismatch parameter. Mean values for the maneuvers performed in the VTS by each of the subjects and comparison with reference values based on the average of the values for the two instructors (subjects 4 and 5).

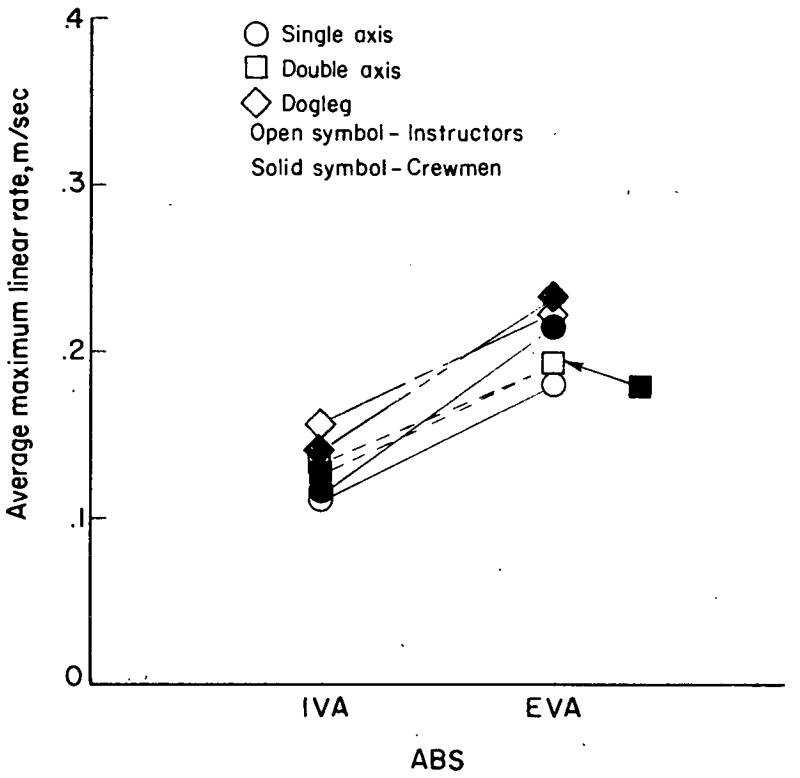


Figure 18.- Group average maximum translation rates for each of three maneuvers for the IVA and EVA test conditions of the ABS.

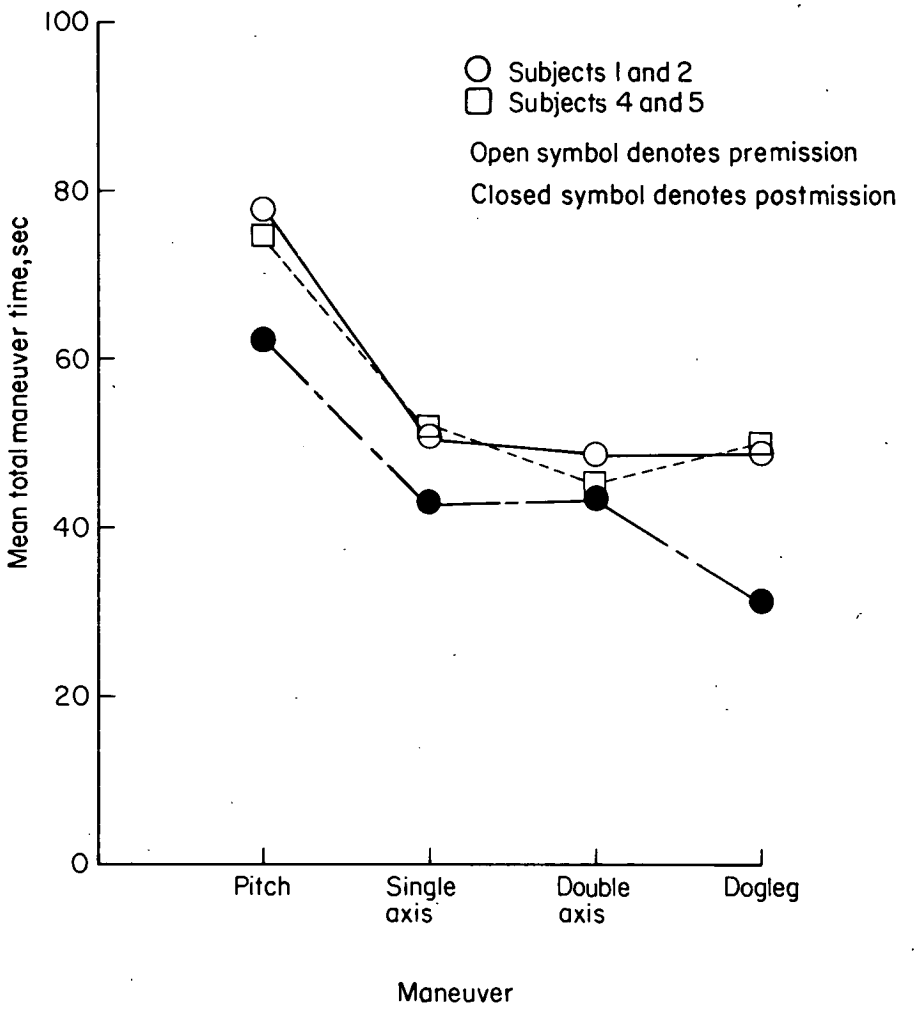


Figure 19.- Comparison of the premission and postmission group mean values for the total maneuvering times for four of the maneuvers performed by the two flight subjects in the ABS. (The group mean values for the two instructors, subjects 4 and 5, are also presented for comparison.)

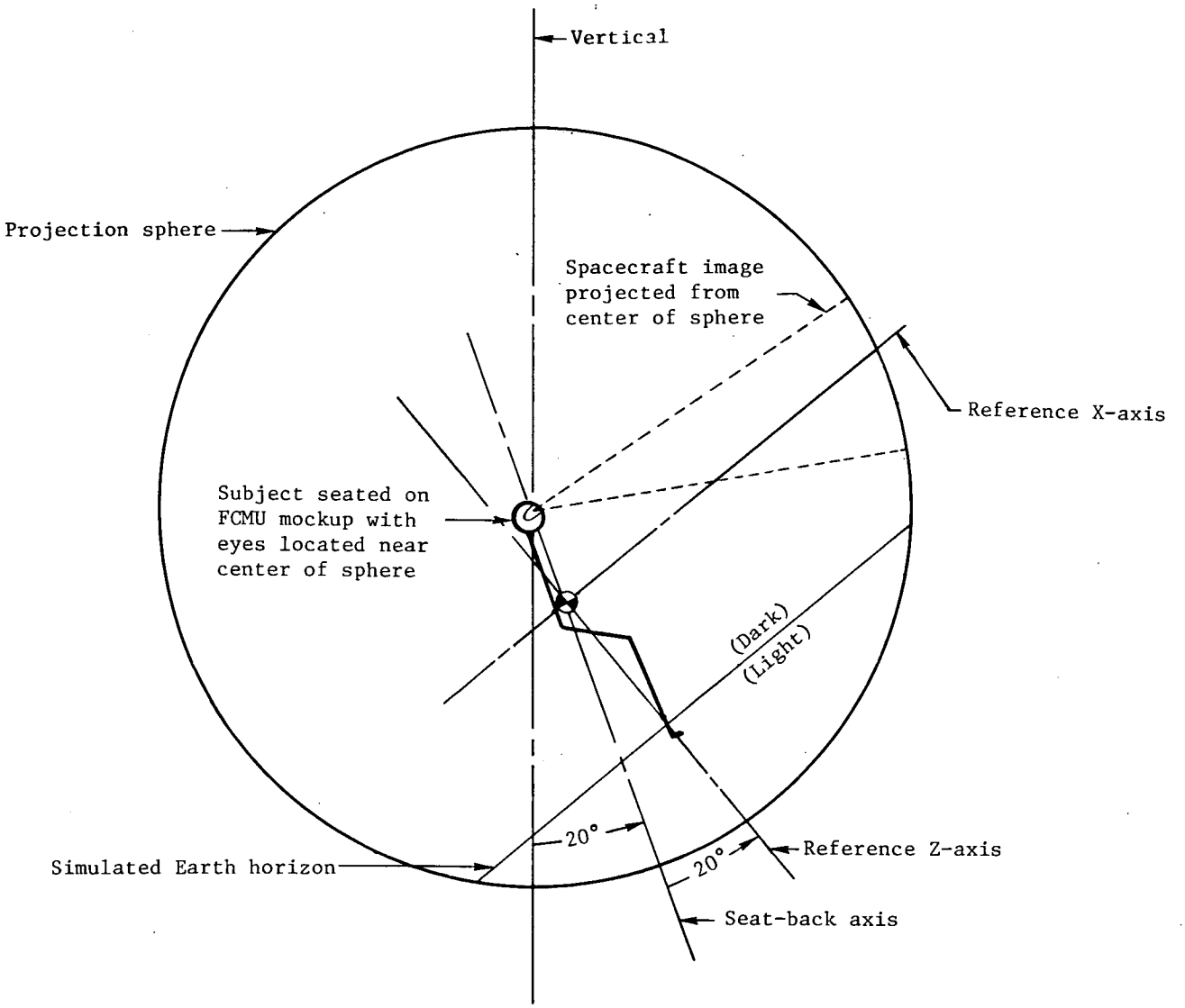


Figure 20.- Diagram of the visual scene and test subject alinement relative to the actual local vertical axis.

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